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DOCTORAL THESIS

Dry Mechanical Processing of Fine Fractions from Enhanced Landfill Mining for Material and Energy Recovery

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WIDMUNG

meinen Eltern und Großeltern, in memoriam.

KURZFASSUNG

Trockenmechanische Aufbereitung von Feinfraktionen aus Enhanced Landfill Mining zur Material- und Energierückgewinnung

Die Feinfraktionen, die je nach Fallstudie normalerweise als das Material mit einer Partikelgröße <60 mm bis <10 mm definiert sind, können 40-80 Gew.-% des gesamten Aushubmaterials in (Enhanced) Landfill Mining ((E)LFM) ausmachen. Diese Fraktionen zeichnen sich häufig durch ihren hohen Gehalt an Wasser und problematischen Elementen und Verbindungen (d.h. organischen und anorganischen Schadstoffen) aus, welche sie für konventionelle Abfallaufbereitungstechniken besonders herausfordernd machen. Daher wurden die Feinfraktionen in früheren (E)LFM-Projekten kaum für die Valorisierungsstrategien Waste-to-Material (WtM) und Waste-to-Energy (WtE) berücksichtigt und folglich größtenteils wieder auf der Deponie entsorgt, was die wirtschaftliche und ökologische Durchführbarkeit des Deponierückbaus in erheblichem Maße beeinträchtigt. Deshalb ist es von entscheidender Bedeutung, die Herausforderung anzugehen, die die Feinfraktionen für (E)LFM darstellen, und ihr Potenzial für Material- und Energierückgewinnung freizusetzen. Die vorliegende Doktorarbeit wurde im Rahmen des „EU Training Network for Resource Recovery through Enhanced Landfill Mining - NEW-MINE“ durchgeführt, welches die Deponie in Mont-Saint-Guibert (MSG), Belgien, als Hauptfallstudie für die Untersuchung der vollständigen Umsetzung des ELFM-Konzepts auswählte. Die Feinfraktionen <90 mm der MSG-Deponie machten 77 Gew.-% (im Rohzustand) des gesamten aufbereiteten Deponieabfalls aus und zeigten einen mittleren Wassergehalt von 27 Gew.-% und eine mittlere Schüttdichte von 810 kg/m^3. Die Ergebnisse dieser Arbeit zeigen, dass die Feinfraktionen <90 mm mittels einer trockenmechanischen Aufbereitung effektiv und effizient in brennbare (9.0 Gew.-% TS), inerte (37.2 Gew.-% TS) und bodenähnliche (42.7 Gew.-% TS) Fraktionen getrennt werden können, sowie dass diese Fraktionen eine Quelle für relevante Mengen an Eisen- (1.4 Gew.-% TS) und Nichteisenmetallen (0.3 Gew.-% TS) sein können. Die angewandte trockenmechanische Aufbereitung wurde in zwei Ansätze unterteilt: der Ansatz für die Feinfraktionen 90-10 mm und der Ansatz für die Feinfraktionen <4.5 mm. Der Ansatz der Feinfraktionen 90-10 mm wurde im optimalen Wassergehalt (Wassergehalt von 15 Gew.-%) und im trockenen Zustand durchgeführt, während der Ansatz der Feinfraktionen <4.5 mm in trockenem Zustand durchgeführt werden musste. Der optimale Wassergehalt erwies sich als ein erfolgreicher Weg, um Materialverluste in der Form von Staub und feinen Partikeln signifikant zu reduzieren, ohne die Leistung des trockenmechanischen Aufbereitungsansatzes signifikant negativ zu beeinflussen. Dieser Zustand war jedoch mit höheren Mengen an Oberflächenanhaftungen und Agglomeraten (d.h. Verunreinigungen) verbunden, welche die Qualität der erzeugten Fraktionen (d.h. brennbare, inerte, bodenähnliche und metallische Fraktionen) geringfügig verringerte. Die Ergebnisse der Laboranalysen der erhaltenen brennbaren Fraktionen zeigen, dass diese Fraktionen den Spezifikationen der EN 15359:2011 entsprachen und somit für WtE-Valorisierung in der EU geeignet sind. Für die EU-Mitgliedstaaten können jedoch

zusätzliche Anforderungen und strengere Grenzwerte gelten. Beispielsweise haben einige Proben der brennbaren Fraktionen die Grenzwerte für As, Cd, Co, Hg und Pb der österreichischen Abfallverbrennungsverordnung (AVV) überschritten, sodass diese Fraktionen in Österreich ausschließlich verbrannt werden können. Daher könnte im Gegensatz zur konventionellen (Mit-)Verbrennungsverfahren ein alternativer Verwertungsweg, wie das vom NEW-MINE-Projekt vorgeschlagene Verfahren (i.e. Plasma-Vergasung/-Pyrolyse) eingesetzt werden, um die Material- und Energierückgewinnung aus solchen Fraktionen zu ermöglichen. Was die zurückgewonnenen inerten Fraktionen betrifft, so zeigen die Ergebnisse, dass in Österreich diese Fraktionen einer weiteren Aufbereitung benötigen, um als Ersatz für Gesteinskörnungen gemäß der österreichischen Recycling-Baustoffverordnung (RBV) genutzt zu werden, da sie den Grenzwert für Kohlenwasserstoffe, Cd, Pb, Zn, NH_4^+ und anionische Tenside in bestimmten Fällen überschreiten. Der angewandte Ansatz für die Feinfraktionen <4.5 mm ergab, dass problematische Schadstoffe (hauptsächlich TOC, Cd, Cu, Hg, Ni, Pb und Zn) aus den groben Partikelgrößenspannbreiten (i.e. 4.5-1.6 mm und 1.6-0.5 mm) nicht ausreichend entfernt oder in den feineren Partikelgrößenspannbreiten (i.e. 0.5-0.18 mm und <0.18 mm) mittels Partikelgrößenklassifizierung und Oberflächenreinigungs-aufbereitungsschritten konzentriert werden können. Die Ergebnisse zeigen, dass Cd, Cu, Hg, Pb und Zn in schwerlöslichen Mineralphasen fest gebunden und/oder stark an Mineraloberflächen adsorbiert sind. Dies behindert die Valorisierung dieser Fraktionen als Bodenersatz in Bauanwendungen in Ländern, in denen Grenzwerte für Pseudo-Gesamtgehalte reguliert sind, z. B. in Österreich. Die Gehalte an TOC und Ni waren wiederum gleichmäßig auf die Partikelgrößenspannbreiten verteilt und ihre Konzentrationen müssten verringert werden, um diese Fraktionen in Österreich zu verwenden. Die Auslaugungskonzentrationen der meisten analysierten Schwermetalle lagen unter den geltenden österreichischen Grenzwerten. Darüber hinaus zeigen die Ergebnisse der Feststofflaboranalysen und Auslaugungstests, dass es keine signifikanten Unterschiede hinsichtlich der Verteilung der Schadstoffe zwischen den verschiedenen Partikelgrößenspannbreiten gab, was die Möglichkeit eröffnet, den alten Teil der Deponie Mont-Saint-Guibert vollständig rückzubauen; vorausgesetzt, dass in Belgien eine geeignete Anwendungs- oder Verwertungsroute für diese Fraktionen gefunden werden kann und dass die geltenden Anforderungen für solche Route erfüllt werden können. Im Allgemeinen ist die Verwertung/Verwertung von zurückgewonnenen Materialien durch (E)LFM nicht ausdrücklich in bestehenden Vorschriften enthalten, und bis heute gelten auf EU-Ebene fast keine übergreifenden Vorschriften. Daher hängen momentan die WtM- und WtE-Verwertungswege aus den zurückgewonnenen Fraktionen der Feinfraktionen von Deponierückbau stark von den nationalen und lokalen Vorschriften in der EU ab.

ABSTRACT

Dry Mechanical Processing of Fine Fractions from Enhanced Landfill Mining for Material and Energy Recovery

The fine fractions, typically defined as the material with particle sizes <60 mm to <10 mm depending on the case study, can account for 40-80 wt.% of the total excavated waste in (enhanced) landfill mining ((E)LFM). These fractions are frequently characterized by their high contents of water and problematic elements and compounds (i.e. organic and inorganic pollutants), which make them particularly challenging for conventional waste processing techniques. Hence, the fine fractions have been largely left out of the scope of waste-to-material (WtM) and waste-to-energy (WtE) valorization strategies in previous (E)LFM projects and, thus, they have been mostly disposed of back in the landfill: hindering the economic and environmental feasibility of those projects in a significant manner. Therefore, to address the challenge that the fine fractions pose to (E)LFM and unlock their potential for material and energy recovery is of critical importance. The present doctoral thesis was carried out within the framework of the EU Training Network for Resource Recovery through Enhanced Landfill Mining – NEW-MINE, which selected the landfill site in Mont-Saint-Guibert (MSG), Belgium, as main case study to investigate the complete implementation of the ELFM concept. The fine fractions <90 mm of the MSG landfill accounted for 77 wt.% (in raw state) of the total processed landfill-mined waste and presented a median water content of 27 wt.%, and a median bulk density of 810 kg/m^3. The results of this thesis demonstrate that the fine fractions <90 mm can be separated into combustible (9.0 wt.% DM), inert (37.2 wt.% DM) and soil-like (42.7 wt.% DM) fractions by means of dry mechanical processing in an effective and efficient manner, as well as that the these fractions can be a source of relevant amounts of ferrous (1.4 wt.% DM) and non-ferrous (0.3 wt.% DM) metals. The employed dry mechanical processing was divided into two approaches: the approach for the fine fractions 90-10 mm and the one for the fine fractions <4.5 mm. The dry mechanical processing approach of the fine fractions 90-10 mm was performed in both the optimal water content (water content of 15 wt.%) and dry states, while the approach of the fine fractions <4.5 mm required to be carried out in dry state. The optimal water content state proved to be a successful way to significantly reduce material losses in the form of dust and fine-sized particles, without having a significant negative impact on the performance of the dry mechanical processing approach. However, that state was associated with higher amounts of surface defilements and agglomerates (i.e. impurities), which slightly decreased the quality of the output fractions. The results of the laboratory analyses of the obtained combustible fractions show that these fractions complied with the specifications of the EN 15359:2011 and, thus, are suitable for WtE valorization in the EU. However, additional requirements and stricter limits may apply among EU member states. For instance, some samples of the combustible fractions exceeded the limit values for As, Cd, Co, Hg and Pb of the Austrian Waste Incineration Ordinance (AVV) and, hence, these fractions can only be incinerated in Austria. Therefore, in contrast to conventional (co-)incineration, an

alternative valorization route, such as the one proposed by the NEW-MINE project (i.e. plasma gasification/pyrolysis), could be employed to enable material and energy recovery from such fractions. As for the recovered inert fractions, results unveil that in Austria these fractions would need further treatment in order to be valorized as a substitute for construction aggregates according to the Austrian Recycling Building Materials Ordinance (RBV), since they exceed the limit values for hydrocarbons, Cd, Pb, Zn, NH_4^+ and anionic surfactants in certain cases. In turn, the employed approach to the fine fractions <4.5 mm revealed that problematic pollutants (mainly TOC, Cd, Cu, Hg, Ni, Pb and Zn) cannot be sufficiently removed from the coarse particle size ranges (i.e. 4.5-1.6 mm and 1.6-0.5 mm) and concentrated in the finer ones (i.e. 0.5-0.18 mm and <0.18 mm) solely by means of particle size classification and surface cleaning processing steps. Results show that Cd, Cu, Hg, Pb and Zn are tightly bound in low-soluble mineral phases and/or strongly adsorbed to mineral surfaces, which hampers the valorization of these fractions as soil substitute in construction applications in countries in which limit values for pseudo-total contents are regulated, such as Austria. In turn, TOC and Ni were found fairly distributed among the particle size ranges and their concentrations would need to be decreased in order to be valorized in Austria as well. The leaching concentrations of most analyzed heavy metals were below the applicable Austrian limit values. Additionally, the results of the solid matter laboratory analyses and leaching tests reveal that there were no significant variations regarding the distribution of pollutants among the different particle size ranges, which opens the possibility to fully implement land reclamation at the old part of the landfill of this case study, provided that a suitable application or valorization route can be found in Belgium for these fractions and that the applicable requirements for such route can be met. In general, the valorization/utilization of recovered materials through (E)LFM is not specifically included in existing regulations and, to this day, there are almost no overarching regulations applicable at EU level. Therefore, WtM and WtE valorization routes from the recovered fractions of the fine fractions of landfill-mined waste are strongly dependent on national and local regulations in the EU.

PUBLICATIONS

The published scientific conference papers and journal articles, as well as the conference presentations and posters, produced in the course of this doctoral thesis are listed below.

Conference papers

Hernández Parrodi, J.C., Höllen, D., Pomberger, R., 2017. Characterization of Fine Fractions from Landfill Mining: A Review of Previous Landfill Mining Investigations, in: Proceedings of the 16th International Waste Management and Landfill Symposium. 16th International Waste Management and Landfill Symposium (Sardinia 2017), Cagliari, Italy. 5-9 October. CISA Publisher, Padova, Italy.

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TABLE OF CONTENTS

1 INTRODUCTION

For a long time a waste or residue was regarded as a worthless, unwanted and/or unusable material that has been discarded or disposed of (Tchobanoglous et al., 1993). However, present times require a more comprehensive, but also precise definition for the concept of waste. As defined in Kranert, 2017, waste is a tangible material that is included in the waste groups and types according to the legal provisions of the circular economy and waste management regulations and the waste catalog ordinance, and whose owner discards, intends to or has to discard. In the present doctoral thesis waste is to be understood according to the latter definition, especially because waste cannot be generally categorized as a worthless nor unusable material in the contemporary world.

In retrospect, the generation and accumulation of increasing amounts of anthropogenic waste on Earth has gone hand in hand with human evolution. The development of settlings into metropolis, industrial revolution, globalization, capitalism and the growing tendency in global consumption, as well as the continuous rise in human population and the ceaseless transition of goods into more complex products, have been among the most significant factors challenging waste management around the world. According to Kurth et al., 2018, waste management is a largely well-ordered system with clear goals and legal bases, defined responsibilities, qualified institutions, waste disposal and service providers, regulated planning and approval procedures, practice-oriented training courses and a secure set of instruments to cover investments and the ongoing costs of recycling and disposal.

To this day the most common way of waste disposal worldwide corresponds to landfilling (US EPA, 2008). Landfills are physical facilities used for the permanent storage of waste, where waste is disposed of on or in the earth´s mantle (Tchobanoglous et al., 1993). While stored in landfills, waste undergoes a series of physical, chemical and biological degradation processes during a long period of time, which in turn can produce diverse problematic elements and compounds (e.g. greenhouse gases, polycyclic aromatic hydrocarbons, polychlorinated biphenyls and heavy metals) that if released into the environment (i.e. air, water and soil) may cause severe pollution issues (Belevi and Baccini, 1989; Bilitewski and Härdtle, 2013; Bozkurt et al., 1999; Martensson et al., 1999; Meegoda et al., 2016; Tchobanoglous et al., 1993). Among the most common negative environmental and health hazards posed by landfills are: the uncontrolled release of landfill gases, leachate, and windblown litter and particulate matter into the environment, the breeding and harboring of vermin and disease vectors, and the release of trace substances arising from the decomposition of hazardous waste (Tchobanoglous et al., 1993). Therefore, landfills can be a critical source of pollution and a threat to the wellbeing of the environment and living things, in particular wild dumpsites and old landfills, and thus they are the least desirable means of dealing with anthropogenic waste. It is estimated that there are more than 500 000 landfills in Europe, from which about 90 % of them are non-sanitary landfills that predate the EU Landfill Directive of 1999 (EURELCO, 2018). Moreover, around 80 % of Europe´s landfills are publicly owned and predominantly contain municipal solid waste, while the remaining 20 % are privately owned and mainly store commercial and industrial waste (EURELCO, 2018). The costs of operation, maintenance, monitoring, closure, aftercare and environmental pollution mitigation and remediation of publicly owned landfills are mostly covered by public resources, which in turn are collected through taxation systems. Therefore, nowadays a significant amount of taxpayer money still ends up being allocated to landfills in the long run, as landfill costs are typically to be maintained for periods of time in the range of decades after their operational lifetime has ended (Tchobanoglous et al., 1993).

Particularly over the last two decades waste has become a topic in vogue, since public awareness of the necessity to protect human health and the environment, as well as the importance of energy and resources conservation, has significantly grown along our way towards a sustainable and more efficient waste management, which is of key relevance in order to achieve a circular economy (Bilitewski and Härdtle, 2013; Kranert, 2017; Kurth et al., 2018; Martens and Goldmann, 2016; Townsend et al., 2015). In a circular economy waste materials are seen as secondary raw materials, which are reincorporated into production processes in the attempt to form a closed cycle between manufacturing and end-of-life of goods (Kranert, 2017; Kurth et al., 2018). From this point of view, materials (e.g. construction aggregates, glass, and ferrous and non-ferrous metals) and energy (e.g. alternative fuels, such as refuse derived fuel (RDF) and solid recovered fuel (SRF)) could be recovered by extracting and processing waste disposed of in landfills and dumpsites: this activity is known as landfill mining (LFM). In addition, LFM can also be driven by the regain of landfill capacity, land reclamation and pollution mitigation and remediation, among others (Bilitewski and Härdtle, 2013; Brammer et al., 1997; Breitenstein, 2017; Cossu et al., 2012; Krook and Baas, 2013; Krüger et al., 2016). However, over time LFM has faced challenging and growing obstacles related to the high costs for its implementation, increasingly stringent regulations and standards in the waste management sector and the production industry, as well as the low amount and quality of the recoverable materials in some cases (Krook et al., 2012).

Therefore, LFM has evolved into a holistic concept called enhanced landfill mining (ELFM) over the last decade, which includes the safe conditioning, excavation and integrated valorization of landfill-mined waste as both materials (Waste-to-Material (WtM)) and energy (Waste-to-Energy (WtE)), by means of innovative transformation technologies, while respecting the most stringent social and environmental criteria, in addition to the common drivers of LFM (Cossu et al., 2012; Cossu and van der Sloot, 2014; Jones et al., 2010; Jones and Tielemans, 2010; Krook et al., 2012; Krüger et al., 2016). In order to further investigate the full implementation of ELFM, the European Union´s Horizon 2020 Research and Innovation Programme within the framework of the Marie Skłodowska-Curie actions (MSCAs) has funded the “EU Training Network for Resource Recovery through Enhanced Landfill Mining – NEW-MINE” under the Grant Agreement No. 721185. The NEW-MINE project follows a value-chain approach from innovative landfill exploration and mechanical processing, to advanced thermochemical conversion and upcycling of by-products and residues, while a multi-criteria assessment compares combined resource-recovery/remediation ELFM methods with existing alternative scenarios, such as “do-nothing” or “business as usual”, “classic remediation” and “classic landfill mining with (co-)incineration”.

1.1 Problem Formulation

In (E)LFM the excavated waste undergoes a series of various processing steps that sort the waste into different material fractions according to their physico-chemical properties (Bilitewski and Härdtle, 2013; Brammer et al., 1997; Breitenstein, 2017; Krüger et al., 2016). Ideally, the obtained material fractions are suitable to be valorized through WtM and WtE schemes after processing. Frequently, one of the initial types of the material processing corresponds to particle size classification (Hogland, 2002; Hull et al., 2005; Kurian et al., 2003; Quaghebeur et al., 2013; Stessel and Murphy, 1992), which is a mechanical process that separates the material into particle size ranges according to preselected cut-off diameters or particle sizes (Bunge, 2012; Martens and Goldmann, 2016). In this process the particle size range from which the material is to be regarded as coarse-sized and fine-sized is defined. Subsequently, the coarse and fine fractions are commonly further processed following different approaches, since their characteristics can significantly differ from each other (Brammer et al., 1997; Breitenstein, 2017; Krüger et al., 2016). Apart from their particle size ranges, the coarse and fine fractions can present considerable differences in amount, composition, bulk density, water content, particle size distribution, and amount of surface defilements and impurities (Brammer et al., 1997; Breitenstein, 2017; Krüger et al., 2016), among others.

Typically, the fine fractions account for the largest share of the excavated material in (E)LFM (Brammer et al., 1997; Breitenstein, 2017; Krüger et al., 2016). In addition, these fractions tend to have higher water content, bulk density and amount of impurities than the coarse fractions (Bhatnagar et al., 2017; Gutiérrez-Gutiérrez et al., 2015; Hogland et al., 2004; Hull et al., 2005; Jani et al., 2016; Kaartinen et al., 2013; Kaczala et al., 2017; Kurian et al., 2003; Masi et al., 2014; Mönkäre et al., 2016; Prechthai et al., 2008; Quaghebeur et al., 2013; Wolfsberger et al., 2015; Zhao et al., 2007). In turn, surface defilements and impurities can be associated with the presence of organic and inorganic pollutants, as well as with efficiency losses in the mechanical processing steps (Bhatnagar et al., 2017; Canopoli et al., 2018; Hogland et al., 2004; Hull et al., 2005; Jain et al., 2005; Jani et al., 2016; Kaartinen et al., 2013; Kaczala et al., 2017; Kurian et al., 2003; Masi et al., 2014; Maul and Pretz, 2016; Prechthai et al., 2008; Quaghebeur et al., 2013; Wolfsberger et al., 2015; Zhao et al., 2007). The previous factors can play a significant role in the processing of the material and, hence, can directly affect the extent, quality and potential value of the recovered materials and energy from the fine fractions in a negative manner. Hence, one commonly chosen alternative in previous LFM projects has been to classify the fine fractions as a residual fraction and dispose them back in a landfill (Bhatnagar et al., 2017; Kaartinen et al., 2013; Münnich et al., 2013). This situation has left the fine fractions out of the schemes of material and energy recovery, which has had a critical impact on the economic and environmental feasibility of LFM projects.

Therefore, the fine fractions belong to the greatest challenges faced by (E)LFM and it is of utmost importance to further investigate their characteristics, in order to find a way to integrate them into the scope of future projects. This integration is to be done in such a way that the extent of the valorization of the fine fractions is maximized and, thereby, the residual amount to be re-disposed of or stored until more suitable technologies for their valorization are developed is minimized. In particular, the present doctoral thesis focuses on the application of a specific dry mechanical processing approach to the fine fractions obtained from a landfill site in Belgium through the full implementation of ELFM. This in order to unlock the potential of the fine fractions for material and energy recovery and provide with first-hand information and data on the amount, characteristics and quality of the obtained material fractions for the multi-criteria assessment of the potential contribution of the fine fractions to the overall economic and environmental feasibility of ELFM.

1.2 Framework of Doctoral Thesis

The present doctoral thesis corresponds to a cumulative dissertation in which the research topic in question is addressed in 10 peer-reviewed scientific articles. These scientific articles have been published in the Multidisciplinary Journal for Waste Resources & Residues – Detritus. An overview of the structure and scientific articles of this doctoral thesis is schematically presented in Figure 1.

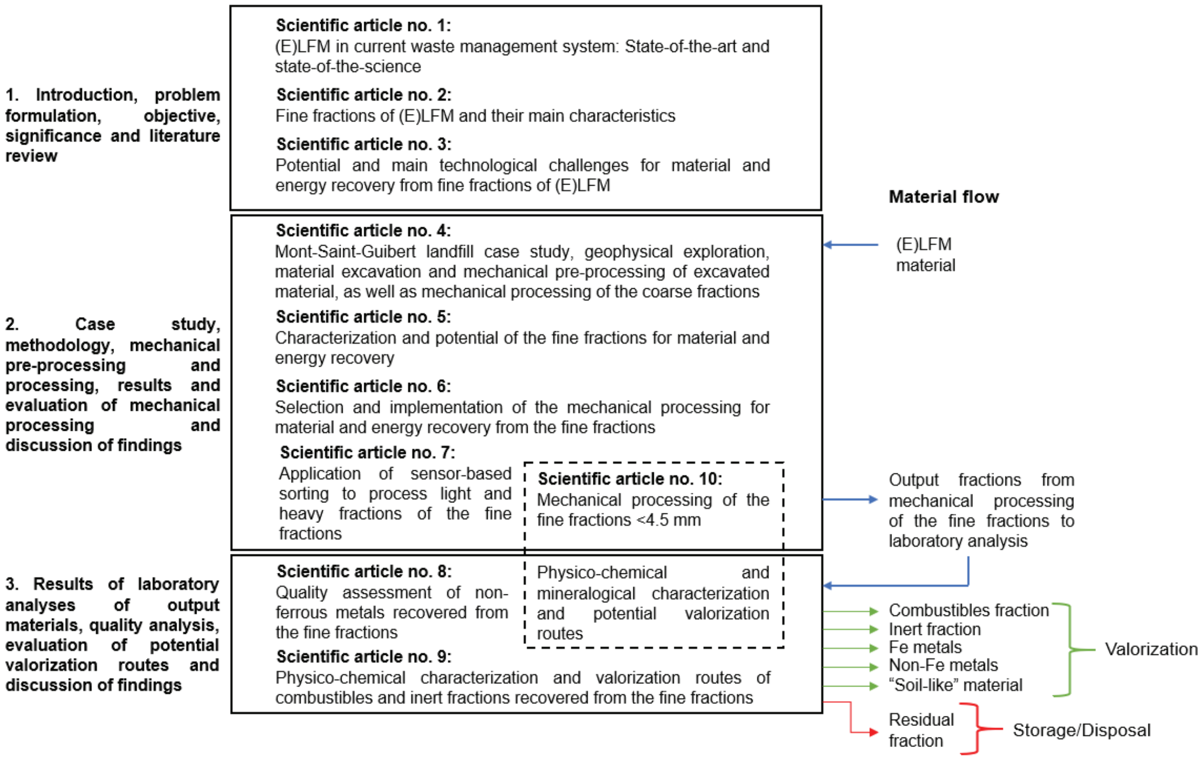

Figure 1: Structure scheme of the doctoral thesis.

The thesis is divided into 3 parts: 1) Introduction, problem formulation, objective, significance and literature review, 2) Case study, methodology, mechanical pre-processing and processing, results and evaluation of mechanical processing and discussion of findings, and 3) Results of laboratory analyses of output materials, quality analysis, evaluation of potential valorization routes and discussion of findings.

The first part (theoretical part) is composed of 3 scientific review articles (i.e. scientific articles no. 1, 2 and 3), which aim to familiarize the reader with (E)LFM, the fine fractions and their main characteristics, as well as to discuss the most relevant issues and challenges to overcome related to these fractions. The scope, importance and purpose of the present investigation are introduced in the first part as well.

In turn, the second and third parts address the objectives of this doctoral thesis in a practical manner through the investigation of a single case study. The second part is comprised of the scientific articles no. 4, 5, 6, 7 and part of the scientific article no. 10, which focus on the main information of the case study, the methodology followed to produce the fine fractions and the determination of their principal characteristics, as well as on the selection of the mechanical processing approach to further process the fine fractions, the evaluation of the obtained results and the discussion of the outcomes. The main properties of the outputs of the employed mechanical processing approaches were determined and evaluated according to some of the applicable regulations in the EU and, in particular, in Austria in the case study papers of the third part, i.e. scientific articles no. 8, 9 and part of the scientific article no. 10. The results of the laboratory analyses are also analyzed and discussed in the third part. The scientific articles of this doctoral thesis are enumerated according to the sequence in which they are suggested to be read.

Regarding the material flow, landfill waste was excavated from the case study landfill and pre-processed to produce the fine fractions. Composite samples of the fine fractions were used to determine their main characteristics and, according to that information, specific mechanical processing methods were selected to separate them into the predetermined material fractions, i.e. combustibles, inert and soil-like materials, as well as ferrous and non-ferrous metals. Samples of the output materials were subjected to laboratory analyses in order to determine their main characteristics and evaluate their suitability for the suggested WtM and WtE valorization routes. A residual fraction was foreseen for the material that cannot be valorized through any of the existing valorization routes and, therefore, this fraction would need to be stored for future further treatment and valorization.

1.3 Scope of Investigation

The scope and main objective of the scientific articles composing the present doctoral thesis are individually presented in the following subchapters in order to provide the reader with the principal issues addressed in each scientific article. The main objective of each scientific article was formulated as a single research question; the answer to that question corresponds to the main outcomes and findings of the scientific article in a synthesized manner. Subsequently, the scientific articles are individually included in their published form as single chapters. Afterwards, an overall summary containing a brief synopsis and answer to the research question of each scientific article is presented. Finally, the general conclusion and the outlook on future research are found as culminating chapters of this dissertation.

Scientific article no. 1

The largely unaddressed problem of legacy landfills and dumpsites in Europe is introduced together with the concepts of LFM and ELFM, and the NEW-MINE project. Also, the main drivers, objectives, importance and principal issues of (E)LFM are presented, and different scenarios for the integration of (E)LFM into current waste management systems in the context of a multidisciplinary approach are discussed. This approach takes into account environmental, economic and societal aspects, in addition to the technical ones. Finally, in this scientific article the current and future potential and main challenges of ELFM are presented and discussed.

Research question: What are the main challenges for (E)LFM and how to integrate it into current waste management?

Scientific article no. 2

Information regarding fine fractions from LFM was gathered from several previous worldwide investigations in order to determine their amount, composition and main characteristics. Early case studies and experiences on the characterization, study and processing of the fine fractions are utilized to identify their current problematic properties and relevance in (E)LFM, as well as to understand the reason why these fractions have been largely discarded with slight or no processing at all in most of the previous projects. This detailed insight into the fine fractions presents the key aspects to be taken into account to successfully address these fractions within the framework of (E)LFM.

Research question: What are the main characteristics of the fine fractions and why are they of utmost importance in (E)LFM?

Scientific article no. 3

Based on the typical characteristics of fine fractions from LFM and experiences from previous studies, the potential of these fractions for valorization in current WtM and WtE schemes is studied and discussed, and specific valorization routes are proposed in this scientific article. Additionally, the current main technological challenges to be overcome to enable material and energy recovery from the fine fractions are presented, as well as the most relevant factors that play a role in the feasibility of (E)LFM projects. The potential shares of the materials recovered from the fine fractions that could be subjected to the proposed valorization routes are discussed as well.

Research question: How could the fine fractions be addressed in (E)LFM and what is the potential of these fractions for material and energy recovery?

Scientific article no. 4

A case study to test the full implementation of ELFM is selected, in which the proposed approach of the NEW-MINE project is carried out. Geophysical explorations of the landfill site are used to select the excavation area, while the landfill-mined waste is pre-processed with a ballistic separator in order to produce the 2-dimensional, 3-dimensional and fine fractions. The 2-dimensional and 3-dimensional fractions are investigated in order to determine their main characteristics and identify potential valorization routes. The fundamental information of the selected case study is presented in this scientific article.

Research question: What are the main characteristics of the excavated material from the Mont-Saint-Guibert landfill and how could this material be initially processed?

Scientific article no. 5

The produced fine fractions through the ballistic separation process in the selected case study are investigated to determine their most important characteristics, such as amount, water content, bulk density, particle size distribution and material composition, as well as the main correlations among them. The key parameters necessary for the design of an adequate mechanical processing of the fine fractions from the selected case study are presented. Additionally, the material and energy recovery schemes identified in the scientific article no. 3 are evaluated and the potential of the fine fractions is discussed in that context.

Research question: What are the main characteristics of the fine fractions of the Mont-Saint-Guibert landfill and what type of materials could be recovered from them?

Scientific article no. 6

According to the findings in the scientific article no. 5, a chain of different mechanical processes is selected to separate the fine fractions into material fractions that could be valorized in the WtM and WtE routes proposed in the scientific article no. 3. An additional study on the influence of the water content on the fine fractions is included, which leads to the study of the selected mechanical processing in 2 different states: the optimal water content state and the dry state. The selected mechanical processes, their configuration and operation parameters are described in detail for both states, as well as the amount of the output materials. The effectivity and efficiency of the implemented mechanical processing are evaluated and discussed for each state as well.

Research question: How could the fine fractions of the Mont-Saint-Guibert landfill be processed to enable material and energy recovery according to the previously identified potential?

Scientific article no. 7

The density separation steps from the mechanical processing separated the fine fractions into light and heavy fractions. The light fractions (fractions to be valorized through WtE) were mainly composed of combustible materials, such as plastic foils, textiles, paper and cardboard; while concrete, bricks, stones and glass constituted most of the heavy fractions (fractions to be valorized through WtM). The presence of high density combustible materials was still observed in the heavy fractions and, therefore, near-infrared (NIR) sorting was employed to remove those materials. The results of the application of NIR sorting in the heavy fractions of the fine fractions are presented and discussed, and the main issues are presented in this scientific article.

Research question: How could high density combustible materials be further removed from the heavy fractions of the fine fractions of the Mont-Saint-Guibert landfill and what are the main challenges of this method?

Scientific article no. 8

Non-ferrous metals belong to those materials with the highest commercial value per unit in (E)LFM. Although they represent a very small share of the landfill-mined waste, their valorization could have a relevant impact in the overall economic feasibility in (E)LFM projects. However, the reported amounts of non-ferrous metals in previous investigations does not correspond to the real amount of material that could be valorized, rather to the amount of these metals combined with organic and inorganic waste and surface defilements, as well as to the amount of these metals that has been oxidized. Therefore, the quality of the recovered non-ferrous metals from the fine fractions is assessed and their marketable recoverable extent is discussed.

Research question: To what extent could the ferrous and non-ferrous metals recovered from the fine fractions of the Mont-Saint-Guibert landfill be valorized and what would be the main challenges?

Scientific article no. 9

Samples of the combustibles and inert fractions recovered from the fine fractions through mechanical processing were subjected to extensive laboratory analyses. These analyses determined the most relevant physical and chemical characteristics of both fractions needed to identify the extent of their suitability for the intended valorization routes, according to the regulations which were considered applicable or the closest to those that could be. The quality of both fractions for each state was evaluated and their suitability for the suggested WtM and WtE schemes is discussed herein.

Research question: To what extent could the combustibles and inert fractions recovered from the fine fractions of the Mont-Saint-Guibert landfill be valorized and what would be the main challenges?

Scientific article no. 10

The selected mechanical processing approach of the fine fractions produced a fraction intended to be used as a substitute for soil in construction applications (fraction to be valorized through WtM). This fraction corresponds to the smallest particle size range (i.e. fine fractions <4.5 mm) obtained; however, it is likely that not all of this fraction can be used in the suggested application due to the presence of organic and inorganic pollutants. Therefore, the fine fractions <4.5 mm were further mechanically processed in order to try to concentrate the problematic elements and compounds in the finest particle size range(s). The outputs of this further mechanical processing were subjected to laboratory analyses in order to determine the main physical, chemical and mineralogical characteristics of these fractions. The results of the laboratory analyses were used to evaluate the performance of the selected further processing and determine if these fractions could follow the intended WtM valorization route.

Research question: How could the fine fractions <4.5 mm of the Mont-Saint-Guibert landfill be further processed to enable material recovery, what are the main characteristics of the produced fractions and to what extent could they be valorized?

2 (ENHANCED) LANDFILL MINING IN THE CONTEXT OF CURRENT WASTE MANAGEMENT

Scientific article no. 1: “Integration of Resource Recovery into Current Waste Management through (Enhanced) Landfill Mining”

Hernández Parrodi, J.C., Lucas, H., Gigantino, M., Sauve, G., Esguerra, J.L., Einhäupl, P., Vollprecht, D., Pomberger, R., Friedrich, B., Van Acker, K., Krook, J., Svensson, N., Van Passel, S., 2019. Integration of Resource Recovery into Current Waste Management through (Enhanced) Landfill Mining. Detritus 8 (1), 141–156. 10.31025/2611-4135/2019.13884.

Annotation on my personal contribution to this scientific article:

I reviewed early LFM studies regarding their main drivers, technical aspects and outcomes and contributed to all 5 chapters of the paper, especially to the first 4 chapters, with the gathered information. I wrote most of the chapters 1 and 2 in collaboration with Hugo Lucas and collaborated with Hugo Lucas and Marco Gigantino in the making of chapters 3 and 4. I revised chapter 5 and collaborated with Giovanna Sauve, John Laurence Esguerra and Paul Einhäupl for its content. In general, the whole content was written in consultation with all 13 authors and all of them reviewed the whole article as well. The revision was mainly performed by me.

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Resources & Residues

INTEGRATION OF RESOURCE RECOVERY INTO CURRENT WASTE MANAGEMENT THROUGH (ENHANCED) LANDFILL MINING

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ABSTRACT

Europe has somewhere between 150,000 and 500,000 landfill sites, with an estimated 90% of them being "non-sanitary" landfills, predating the EU Landfill Directive of 1999/31/EC. These older landfills tend to be filled with municipal solid waste and often lack any environmental protection technology. "Doing nothing", state-of-the-art aftercare or remediating them depends largely on technical, societal and economic conditions which vary between countries. Beside "doing nothing" and landfill aftercare, there are different scenarios in landfill mining, from re-landfilling the waste into "sanitary landfills" to seizing the opportunity for a combined resource-recovery and remediation strategy. This review article addresses present and future issues and potential opportunities for landfill mining as an embedded strategy in current waste management systems through a multi-disciplinary approach. In particular, three general landfill mining strategies are addressed with varying extents of resource recovery. These are discussed in relation to the main targets of landfill mining: (i) reduction of the landfill volume (technical), (ii) reduction of risks and impacts (environmental) and (iii) increase in resource recovery and overall profitability (economic). Geophysical methods could be used to determine the characteristics of the landfilled waste and subsurface structures without the need of an invasive exploration, which could greatly reduce exploration costs and time, as well as be useful to develop a procedure to either discard or select the most appropriate sites for (E)LFM. Material and energy recovery from landfilled waste can be achieved through mechanical processing coupled with thermochemical valorization technologies and residues upcycling techniques. Gasification could enable the upcycling of residues after thermal treatment into a new range of eco-friendly construction materials based on inorganic polymers and glass-ceramics. The multi-criteria assessment is directly influenced by waste- and technology related factors, which together with site-specific conditions, market and regulatory aspects, influence the environmental, economic and societal impacts of (E)LFM projects.

1. INTRODUCTION

From the very beginning of the development of human settlements and the accumulation of residues discarded by their inhabitants, certain places, known today as landfills, have been created for the disposal of waste. Prior to the 1950s, those sites were mostly wild dumpsites in which environmental, health and safety implications were not taken into account, making them critical sources of pollution and posing a threat to the environment (Meegoda et al., 2016).

Research carried out over the last decades as well as growing public awareness have led to modern guidelines and regulations (Meegoda et al., 2016), with an increasing

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tendency for the implementation of an integrated waste management system into a circular economy. However, the role of the landfill in a modern waste management system as an ultimate sink for contaminants is still valid (Brunner, 2004). Nowadays it is well known that landfilled waste undergoes several degradation processes during a long period of time, and with negative environmental implications (Belevi & Baccini, 1989; Bozkurt et al., 1999; Martensson et al., 1999). Leaching of heavy metals and other toxic compounds to soil, surface- and groundwater, gas emissions, such as SO_2, CH_4, CO_2, surface runoff, windblown litter and dust, and proliferation of birds, vermin and insects are among the most common negative environmental and health effects of waste landfilling (Höxter, 2001), if landfill gas and leachate are not properly managed.

Contemporary landfills, known as "sanitary landfills" (Figure 1) are engineered disposal sites designed to minimize adverse environmental and health impacts, while higher safety measures are imposed and the storage of waste is enhanced (e.g. waste compaction and conformation) (EU Landfill Directive 1999/31/EC). Before depositing waste in a sanitary landfill, the place destined to become such a disposal site is carefully selected and its base is covered by a number of protection barriers (e.g. a layer of compacted clay, asphalt and/or synthetic liners), which prevent the infiltration of leachate directly into the ground and groundwater bodies. Additionally, a drainage system is placed at the bottom of the landfill basin, where a network of pipes collects the leachate generated by the disposed waste and transports it to further treatment. Waste disposed of in a landfill is also covered with a low permeability top layer to prevent infiltration of rain water, migration of gaseous emissions, windblown waste, and presence of harmful fauna. An additional pipe network is employed to collect gaseous emissions (i.e. biogas) produced during the biological decomposition of waste (Meegoda et al., 2016). Gaseous emissions, leachate, and groundwater quality in the area of the landfill site are continuously monitored in order to detect problems and, ideally, ensure that no damage is done by the landfilling of waste (Chian & DeWalle, 1976; Meegoda et al., 2016).

However, aftercare activities (i.e. emissions monitoring and treatment and infrastructure maintenance) related to landfill sites need to be carried out over a long period of time, since the potential emissions from landfills can have significant impacts to human health and the environment for decades or even centuries (Laner et al., 2012). Over this long time period, the space used by the landfill remains occupied and unavailable for certain uses, e.g. due to insufficient geotechnical stability, which leads to paramount costs and blocked capital. Moreover, control and protection barriers in sanitary landfills may eventually fail and, alike in non-sanitary landfills or wild dumpsites, liquid, gaseous and solid emissions can be released into the environment (Laner et al., 2011b; Pivato, 2011).

Despite being an apparently low cost and relatively simple waste management disposal method, the role of waste landfilling in a circular economy model is more restricted to that of an ultimate sink of contaminants. If landfill aftercare is not conducted adequately, even contemporary landfills might represent an environmental and health hazard.

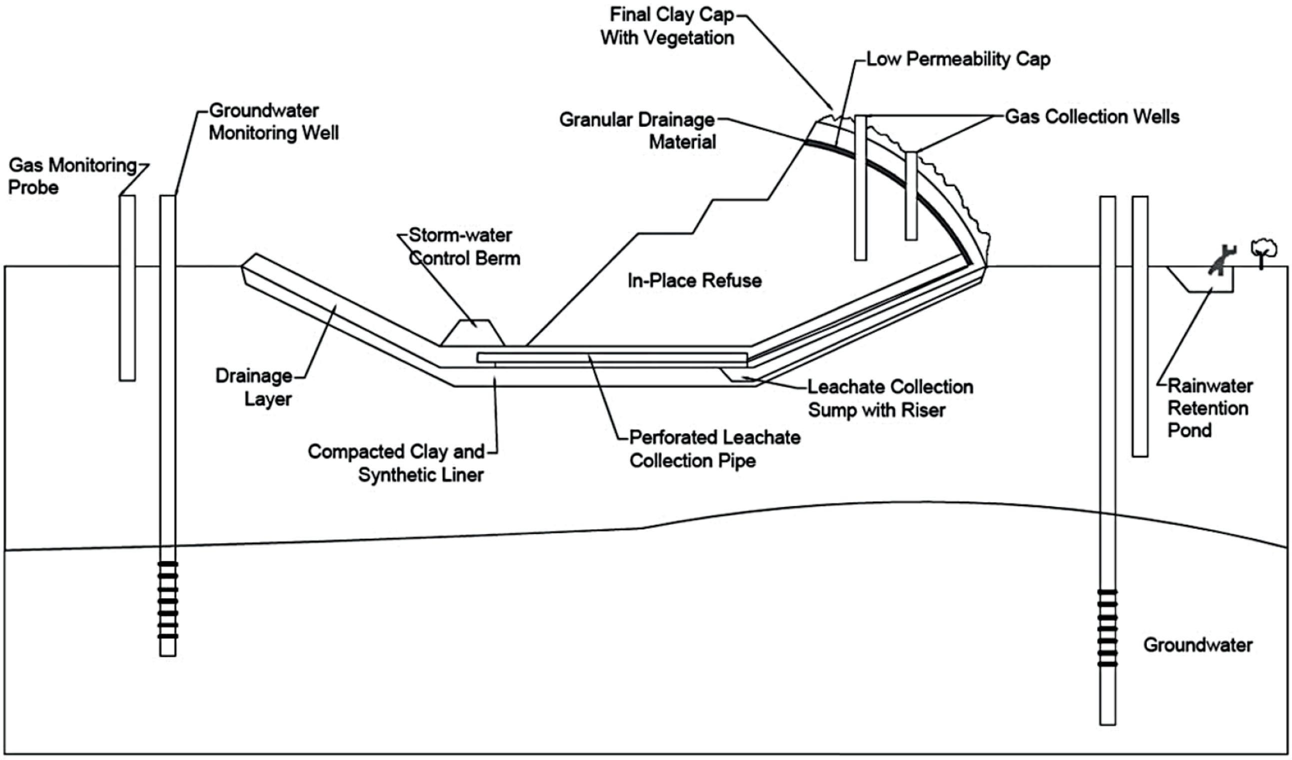

FIGURE 1: Cross-section of a contemporary sanitary landfill (Meegoda et al., 2016).

2. LANDFILL MINING

The extraction of waste from disposal sites for the recovery of certain materials is far from being a novel and unprecedented concept. It is, in fact, a relatively well-known and widespread practice that has been carried out in many countries over the last six decades, which is known as landfill mining (LFM). There are several definitions of LFM; the first one was introduced by Cossu et al., 1996, in which LFM was defined as "the excavation and treatment of waste from an active or inactive landfill for one or more of the following purposes: conservation of landfill space, reduction in landfill area, elimination of a potential contamination source, mitigation of an existing contamination source, energy recovery from excavated waste, reuse of recovered materials, reduction in waste management system costs and site re-development". As defined by Krook et al., 2012, LFM is "a process for extracting materials or other solid natural resources from waste materials that previously have been disposed of by burying them in the ground". More than half a century has passed from the beginning of LFM projects (Savage et al., 1993) and the drivers for LFM have spanned from regaining landfill capacity to recovering valuable materials, such as organic matter for soil improvement purposes, refuse derived fuel (RDF) and metals (Hogland, 2002; Prechthai et al., 2008; Savage et al., 1993; Shual, 1958; Van der Zee et al., 2004). As confirmed by Krook et al., 2012, "landfill mining has primarily been seen as a way to solve traditional management issues related to landfills such as lack of landfill space and local pollution concerns. Although most initiatives have involved some recovery of deposited resources, mainly cover-soil and in some cases waste fuel, recycling efforts have often been largely secondary".

In general terms, LFM projects have focused on expanding landfill lifetime and consolidating landfill area to facilitate the closure and remediation of those sites (Cha et al., 1997; Dickinson, 1995; Krogmann & Qu, 1997; Spencer, 1990). The recovery of land and materials represent important drivers for LFM, together with the potential to reduce surface-, groundwater and soil contamination by remediating the landfill (Marella & Raga, 2014). This could also contribute to the reduction of aftercare costs and other pollution-related costs. Although the mentioned factors represent important drivers for LFM, the excavation and material valorization processes could also lead to additional costs and impacts (Hermann et al., 2016). Moreover, LFM has faced great and growing challenges over time, many of them led by low amount and quality of high-value materials present in landfill sites, high costs for its implementation and increasingly stringent regulation in the waste management sector, as well as raising standards in the production industry (Krook et al., 2012).

2.1 Scenarios of LFM

Within the framework of the "EU Training Network for Resource Recovery through Enhanced Landfill Mining – NEW-MINE" (NEW-MINE), LFM has been classified in four scenarios, namely "Do-Nothing", "Classic remediation with relandfill", "Classic landfill mining with RDF state-of-the-art (co-)incineration" and "NEW-MINE" scenarios. The routes followed by each scenario, as well as the processes included in those routes are schematized in Figure 2.

2.1.1 "Do-nothing" scenario

As previously mentioned, old landfill sites or wild dumpsites have very few or no protection measures at all to prevent environmental and health damages that contemporary sanitary landfills normally have. Moreover, the containment system of sanitary landfills is likely to fail over time. Therefore, the "Do-nothing" scenario should not really be an option, since it turns a blind eye to the critical risks posed by those sites and leaves the problem unsolved indefinitely. Some basic and relatively inexpensive improvements that can be implemented in those sites could be (Höxter, 2001):

- Definition of dumping areas
- Waste delivery control and documentation
- Volume reduction of disposed waste by means of waste conformation and compaction
- Aerobic pre-treatment of waste to reduce methane emission
- Installation of biogas collection system
- Installation of groundwater wells for monitoring
- Installation of leachate collection system (if possible)

2.1.2 "Classic remediation with relandfill" scenario

This scenario envisages the extraction of waste from wild dumpsites and old landfills, or problematic sanitary landfill sites, in order to place the excavated waste in a more appropriate disposal site, such as a new or contemporary sanitary landfill. For example, this can be the case due to the need to fulfill modern regulatory requirements and conventional solutions are not able to improve environmental conditions or remediate the problem (Höxter, 2001; Jones et al., 2013, 2018; Van Passel et al., 2013). According to the Flemish Public Waste Agency in Belgium, the costs for landfill remediation for the EU-28 could be as high as 100 billion to 1 trillion euros. This approach is also addressed in the initiative "Closing Dumpsites" of the International Solid Waste Association (ISWA), as the costs for re-landfilling are still far below from those of all alternatives, because the costs for processing might exceed the revenues from potentially recyclable fractions (Winterstetter et al., 2015).

2.1.3 "Classic LFM with RDF state-of-the-art (co-)incineration" scenario

The classic LFM approach is looking not only to remediate the landfill site, but also to minimize remediation costs through the valorization of landfill waste materials. This approach has been largely applied in previous LFM projects, since it also aims to decrease the amount of waste to be re-landfilled; valorizing waste through the separation of materials with high calorific value, such as paper, plastics, textiles and wood, among others, for thermal valorization, and recyclable materials, such as metals and glass, among others, for material valorization. The thermal valorization is carried out mainly by the production of RDF, which is used in (co-)incineration plants to recover energy in the form of

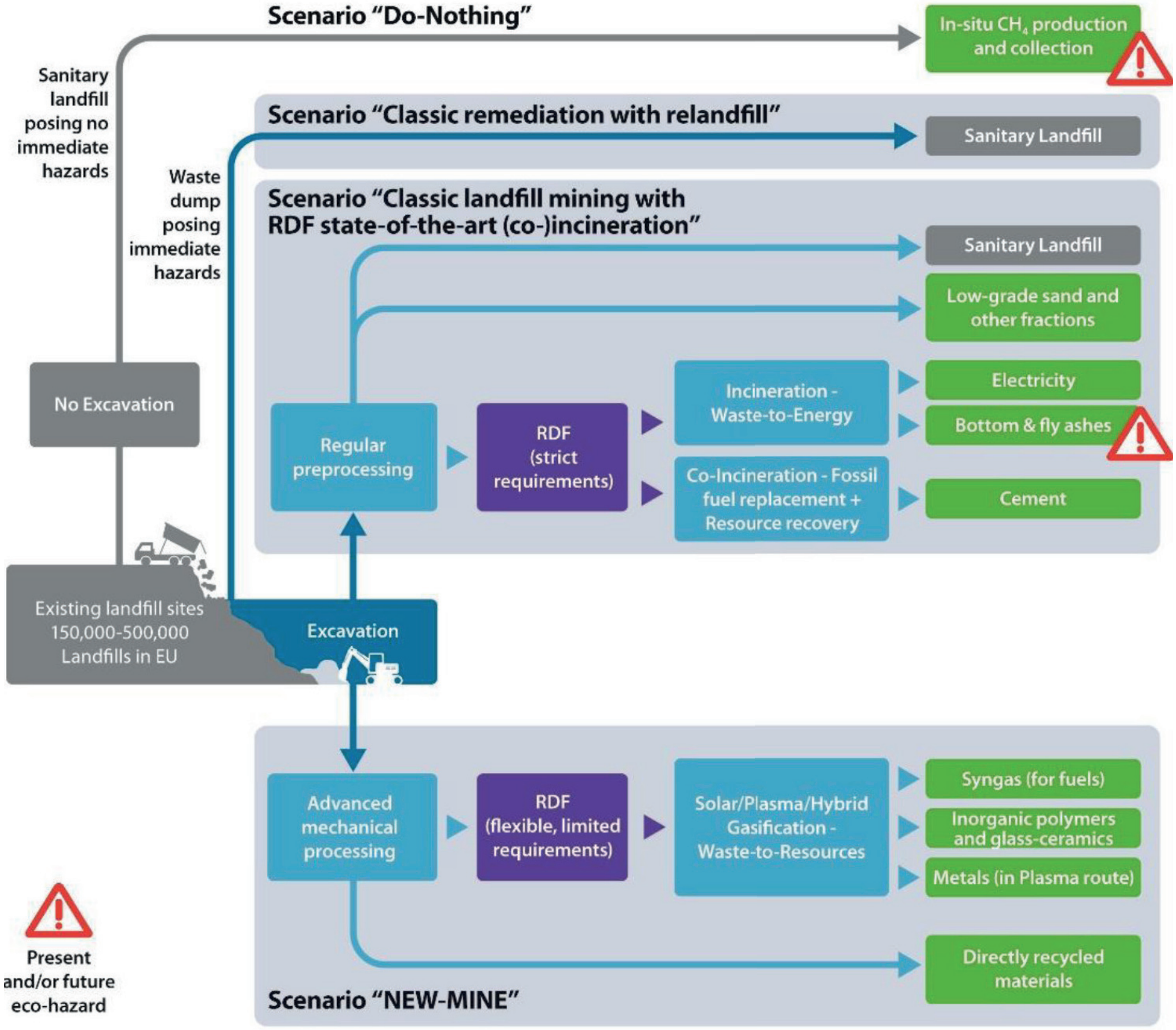

FIGURE 2: LFM scenarios (source: https://new-mine.eu).

heat and electricity (Jones et al., 2013). However, as nowadays prices for RDF are commonly negative, this scenario results less economical than the "Classic remediation with relandfill" scenario.

2.1.4 Enhanced landfill mining or "NEW-MINE" scenario

The need for a common framework to address LFM issues, technological development and further research on this subject has pushed scientists to develop a holistic concept called enhanced landfill mining (ELFM), which is, as defined by Jones et al., 2010, "the safe conditioning, excavation and integrated valorization of (historic and/or future) landfilled waste streams as both materials (Waste-to-Material, WtM) and energy (Waste-to-Energy, WtE), using innovative transformation technologies and respecting the most stringent social and ecological criteria", and has been under development by the Flemish ELFM Consortium since 2008 (Jones et al., 2013). To this end, the European Union´s Horizon 2020 research and innovation programme within the framework of the Marie Skłodowska-Curie actions has funded the NEW-MINE project, which is referred to as "NEW-MINE" scenario in this review article. In the "NEW-MINE" scenario the technological innovation follows a value-chain approach, from advanced landfill exploration, mechanical processing, thermochemical conversion and upcycling, while the multi-criteria assessment methods compare combined resource-recovery/remediation ELFM methods with the previous scenarios: "Do-nothing", "Classic remediation with relandfill" and "Classic LFM with RDF state-of-the-art (co-)incineration". The ELFM concept or "NEW-MINE" scenario is currently under development and the main goal is to insert LFM in a circular economy context, where most of the residues are upcycled and, therefore, minimized.

2.2 Stages in LFM

2.2.1 Site exploration

The material composition and physicochemical properties of the waste disposed of in a landfill site are the preliminary and most important information to be gathered in LFM in order to assess the economic, technical and environmental feasibility of the project. However, it is not rare that there are no records about the type or location of the waste deposited in a landfill. Hence, in the best case, LFM projects need to resort to invasive exploration by means of bore sampling or small scale excavations throughout the whole landfill site; in other cases the available disposal records are used to determine the composition and characteristics of the waste, while in the worst case, no previous analysis is done at all (Hernández Parrodi et al., 2018a). In the case of invasive exploration, the excavated waste samples are classified according to material type and particle size, which are used to determine the amount of material that might be valorized and estimate the remediation costs of the whole site (Bhatnagar et al., 2017; Cha et al., 1997; García López et al., 2019; Hernández Parrodi et al., 2018b; Hogland, 2002). However, certain fractions which might be valorized from fresh waste, may not be valorized from landfilled waste due to degradation and contamination processes in the landfill body.

From an ELFM perspective, geophysical methods, such as the ones used for underground water or petroleum exploration, could be used to determine the material characteristics in a rough manner without the need of an invasive exploration, as well as to identify the most interesting area, in terms of depth, water content and presence of certain materials, before carrying out the extraction of landfilled waste. The characterization of landfill subsurface structures using non-destructive and rapid approaches could greatly reduce the exploration costs (Bobe et al., 2018) and be useful to develop a procedure to either discard or select the most appropriate sites for LFM, according to specific criteria. For example, Figure 3 depicts the characterization of the subsurface structures of a landfill, as well as their electric and dielectric properties. These could allow the identification of the type of material to be expected according to the depth and extent of the landfill, as well as the potential presence of metallic materials and water.

2.2.2 Excavation and material processing

After the exploration of the site and a positive assessment of the feasibility of the site in question for LFM, the excavation of the landfilled waste takes place. This is normally done by using bulldozers to remove the top cover layers and excavators to dig out the landfilled waste. The excavated waste is usually loaded in trucks and transported to the processing plant.

Relatively simple technologies have been employed to process the excavated landfilled material, as for example trommel sieving, magnetic separation, and density classification, which in some cases have shown marginal performance in producing marketable recyclables (Krook

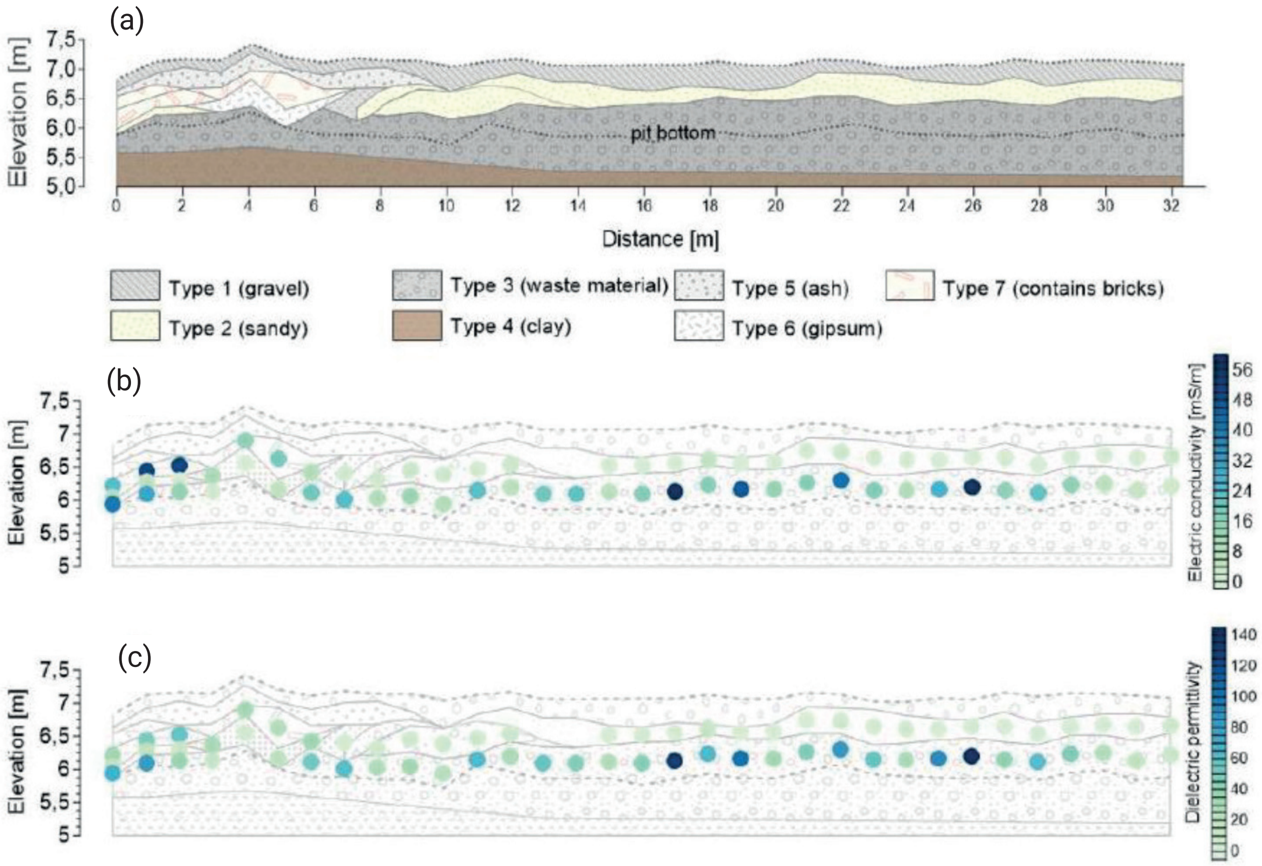

FIGURE 3: Schematic representation of the (a) profile description indicating the main types of material discriminated and (b) profile measurements of electric conductivity and (c) dielectric permittivity (Bobe et al., 2018).

et al., 2012). Moreover, LFM has faced great and growing challenges over time, many of them led by low amount and quality of high-value materials present in landfill sites, high costs for its implementation and increasingly stringent regulation in the waste management sector, as well as raising standards in the production industry (Krook et al., 2012).

Besides the traditional techniques used in traditional LFM projects, new equipment is nowadays being tested with promising results. Ballistic separators can separate landfill waste into three different fractions, namely three-dimensional (3D) and two-dimensional (2D) materials, and an under-screen fraction. This technology can be used to pre-process the landfilled waste directly after excavation and precondition the material for further mechanical processing (García López et al., 2019). Further processing, such as drying, particle size reduction equipment, particle size classification, ferrous and non-ferrous metal separators, density separation methods and sensor-based sorting, could be employed in order to sort the landfilled waste into different material outputs (Hernández Parrodi et al., 2019b; Küppers et al., 2019), such as:

- High calorific value materials (e.g. plastics, wood, textiles, paper and cardboard, among others)
- Ferrous metals (e.g. iron and steel)
- Non-ferrous metals (e.g. Cu, Al, Zn, Pb, Ni, among others)
- Inert materials (e.g. glass, ceramics, and concrete, among others)
- Residual fraction (i.e. normally fraction with finest particle size)

Some of these output flows could be used to recover materials through recycling (e.g. glass, inert materials, ferrous and non-ferrous metals) and to produce an alternative fuel (i.e. high calorific value materials), while a certain amount of the residual fraction might need re-landfilling or further processing (Hernández Parrodi et al., 2018b). Comprehensive studies on the resource potential of LFM materials can be found in Wolfsberger et al., 2015, García López et al., 2019, and Hernández Parrodi et al., 2019a.

In general, there are two main strategies to valorize waste in the current waste management system. The first, known as waste-to-material (WtM), targets recycling of waste, such as plastics, metals and minerals, to replace primary raw materials. The second one, known as waste-to-energy (WtE), aims to valorize waste materials with a high calorific value in (co-)incineration plants to produce thermal and electrical energy.

3. WASTE-TO-MATERIAL

3.1 Metals

Ferrous and non-ferrous metals are considered the most valuable resource extracted from landfills. According to Winterstetter et al., 2015, and Van Vossen & Prent, 2011, those contribute the most to the revenues from LFM. The technology for recycling and upcycling metal scrap is nowadays the most developed compared to that for other waste fractions, such as inert materials or plastics. For this reason, finding a market for metal scraps coming out from landfilled waste is not considered to be a critical issue. Nevertheless, the quality of the recovered metals from landfilled waste does play a relevant role in the extent of their recyclability and marketability, and, hence, is to be taken into account while assessing the recovery potential and economic feasibility in (E)LFM projects.

A detailed study on the quality assessment of the non-ferrous metals recovered from a Belgian landfill can be found in Lucas et al., 2019.

3.2 Inert materials

According to previous investigations, most of the excavated waste in LFM projects corresponds to fine fractions (Hernández Parrodi et al. 2018a). Fine fractions are mostly composed of a mixture of degraded organic matter and weathered inert materials, which, if adequately separated, might be used to produce recycled construction aggregates (e.g. construction sand). The use of inert materials recovered from waste as construction aggregates is regulated by Article 6 of the EU Waste Framework Directive (2008/98/EC), which states a series of criteria to be complied with in order to recycle such recovered materials. However, additional criteria that depend on local legislation might be enforced as well (EU-Report 26769 EN, 2014).

3.3 Plastics and other materials

The recovery of plastic materials from LFM for recycling purposes might be possible; nonetheless, the high degradation state in which these materials are recovered, and their degree of contamination with impurities and surface defilements represent a relevant obstacle to follow the WtM route (Wolfsberger et al., 2015). Therefore, plastics recovered from LFM may result more suitable for the production of RDF, which can be used in WtE co-incineration plants (Bhatnagar et al., 2017).

Other materials, such as organic matter, wood, textile, leather, paper and cardboard cannot be recycled directly to replace primary raw materials due to their level of degradation and contamination, and poor quality (Quaghebeur et al., 2013; Spooren et al., 2013; Wolfsberger et al., 2015) (Table 1).

4. WASTE-TO-ENERGY

Carbonaceous material sorted from landfilled waste, which cannot be recycled directly, can be valorized into energy. Three main thermal treatment technologies have been developed in order to recover energy from municipal solid waste (MSW) and industrial waste (IW): incineration, pyrolysis and gasification (Yan et al., 2016; Kalogirou, 2018).

4.1 Incineration

Incineration is the most widespread and mature WtE technology to dispose of MSW and IW (the combustible solid waste volume can be reduced up to 90%) and, simultaneously, produce electricity and district heating. This process can accept waste without any pre-treatment and in a wide range of compositions and is, therefore, very robust and versatile and relatively simple. Complete combustion

TABLE 1: Overview of the situation with respect to the utilization of waste-derived aggregates in some selected EU Member States (EU-Report 26769 EN, 2014).

Member State	Regulation of the use of waste aggregates?	Criteria on total content?	Criteria on leaching?	Type(s) of leaching tests required?
Austria	Guidelines	Yes	Yes	EN 12457-4 (L/S=10 l/kg)
Belgium	Yes, in the Flemish region	Yes	Yes	CEN/TS 14405 (L/S=10 l/kg)
Czech Republic	Based on Landfill legislation *	Yes	Yes	EN 12457-4 (L/S=10 l/kg)
Denmark	Yes	Yes	Yes	EN 12457-1
Finland	Yes	Yes	Yes	CEN/TS 14405; EN 12457-3 (L/S=10 l/kg)
France	Yes	Yes	Yes	EN 12457-2 and 4**
Germany	Guidelines (new regulation in preparation)	Yes	Yes	EN 12457-2 and DIN 19528 (new legislation)
Hungary	Some	No	Yes	Unknown
Italy	Yes	No	Yes	EN 12457-2 (L/S=10 l/kg)
The Netherlands	Yes	Yes	Yes	CEN/TS 14405 (L/S=10 l/kg)
Poland	No	No	No	Unknown
Portugal	Some guidelines	No	No	Unknown
Slovakia	No	No	No	Unknown
Spain	Yes, regional	No	Yes	EN 12457-4 and DIN 38414-S4
Sweden	Guidelines, case by case	Yes	Yes	CEN/TS 14405 (L/S=10 l/kg)

** Considering adopting Austrian guidelines*
*** For compliance testing (CEN/TS 14405 for basic characterization)*

of the waste is achieved in a controlled oxidizing environment, usually with excess air, at temperatures that can vary from 800ºC to 1200ºC, typically in the range 800-900°C. The carbonaceous solid waste undergoes four consecutive stages: (i) evaporation of the moisture content, (ii) release of volatile hydrocarbons/charcoal formation, (iii) combustion of the volatiles and (iv) combustion of the residual charcoal. The combustion chamber is commonly a moving grate furnace, but also different configurations like fluidized bed and rotary kiln are used. Most of the calorific content of the waste is transferred to flue gases in form of sensible heat and delivered to a downstream power block. Flue gases include products of incomplete combustions (e.g. carbon monoxide, alkenes, organic acids, soot, etc.), particulate matter (usually inorganic salts or oxides mixed with incomplete combustion compounds), acidic gases (HCl, SO_2, SO_3, NO_x, etc.), heavy metals and dioxins. Modern flue gas cleaning systems benefit of a wide range of air pollution control techniques that allow to comply with the strictest admissible environmental emissions limits before discharging into the atmosphere. The residues from waste incineration, in the form of bottom ash and air pollution control residues (APCR), are then treated and recycled, e.g. paving roads, or landfilled (Gleis et al., 2001). The overview of a typical incineration plant is shown in Figure 4.

4.2 Pyrolysis

Pyrolysis and gasification are sub-processes of incineration, but they can also be entirely distinct technologies. Pyrolysis of carbonaceous solid waste consist of its thermal decomposition, typically in the temperature range 300-850°C, in an inert/reducing environment, i.e. with no addition of oxygen. Due to the complex composition of MSW, a multitude of reactions, mainly endothermic, occur simultaneously in the reactor and its output is divided into gaseous products and a solid residue (the so-called char). The first consists mainly of CO and H_2, but includes also CH_4 and other volatile organic compounds (VOCs). A fraction of the latter is condensated and results into liquid products: oils, waxes and tars. The solid residue is a mixture of coke and a non-combustible inorganic fraction and, although it can be further processed to release the energy content of the organic part, typically there is low demand for it. The reactor configuration (fixed bed, fluidized bed, screw kiln, rotary drum, etc.) is selected based on the operation mode (batch, semi-continuous or continuous) and on the method used to deliver the heat, usually transferred indirectly, i.e. by thermal conduction. Although pyrolysis allows to reduce the volume of the waste and simultaneously recover energy from it, due to the low energy outputs obtained in the case of MSW, its industrial scale application is very limited.

4.3 Gasification

In the gasification process, carbonaceous waste reacts with a gasification agent (oxygen and/or steam) at temperature that vary from 700 to 1600°C in partially oxidizing conditions (absence or substoichiometric presence of oxygen) to produce a fuel gas called syngas, which is a mixture of CO and H_2. A significant advantage of gasification is that syngas can be combusted at higher temperatures than those achievable with the original fuel or even in fuel cells, so that the thermodynamic efficiency of the downstream power cycle is enhanced. In addition, problematic chemical elements (e.g. chloride and potassium) can be separated from the syngas, allowing the production of clean combustion flue gases. Furthermore, syngas

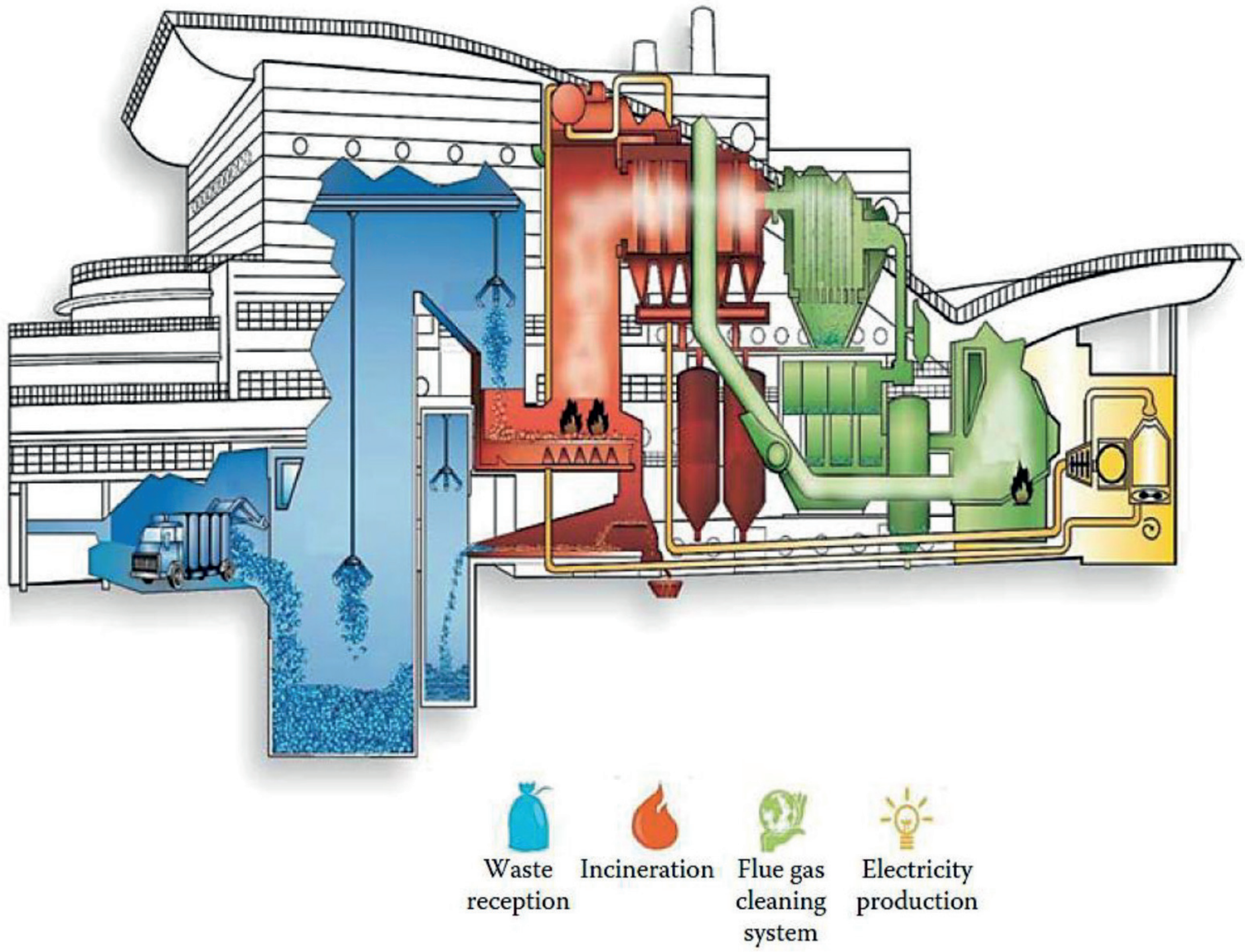

FIGURE 4: Scheme of a MSW incineration plant for power generation (SEVEDE, 2007).

can be stored and used in internal combustion engines or converted into high-purity hydrogen or synthetic fuels. The other products from gasification are a solid inert residue (ash) and tar, which is usually cracked into smaller hydrocarbon molecules in a downstream reactor placed after the gasifier in order to avoid deposit and blockage of the piping. Types of gasifiers include fixed bed, fluidized bed, rotary kiln and other less common configurations. The gasification process consists of several chemical and physical phenomena occurring in series-parallel with each other and, generally, the feedstock is subject to 4 stages (not necessarily carried out in the same reaction chamber): (i) evaporation of the moisture content, (ii) release of volatile hydrocarbons/formation of char (mixture of fixed carbon and inert), (iii) reduction (with steam or hydrogen) of a portion of the fixed carbon with release of hydrocarbons and simultaneous oxidation (with oxygen or steam) of the other fraction of the fixed carbon and some hydrocarbons, (iv) melting of the inorganic residues. The heat released from the exothermic partial oxidation of the waste compensates for the heat absorbed by the endothermic reactions (decomposition and reduction) and for the latent heat of fusion of the inorganic residues. The melting of the ash generates a vitreous inert material that, instead of being landfilled, could be exploited by the construction industry. Considering the potential benefits (e.g. production of a storable and clean energy carrier, significant waste volume reduction and efficient pollution control), gasification has become the most attractive integrated solution for both waste treatment and energy recovery.

4.4 Other emerging gasification technologies

In the “autothermal” gasification part of the waste is oxidized instead of being converted into syngas, in order to drive the chemical and physical phenomena that absorb heat. In the “allothermal” gasification the extraction of the energy content of the waste is maximized by preheating it with an auxiliary energy source: external combustion, electrical energy, solar energy, etc. (Fabry et al., 2013; Sanlisoy et al., 2016; Piatkowski et al., 2011a; Loutzenhiser et al., 2017).

4.4.1 Plasma gasification

Hot plasma, an ionized gas formed by using electrical energy, can contribute to sustain the high-temperature transformations occurring in the gasification process. The maximum temperature achievable by combustion is around 3000 K (for the acetylene-oxygen mixture) while plasma can go up to 15000 K. The higher temperature attained allow to break down nearly all compounds into their elemental form and significantly accelerate the reaction rates, resulting in a higher waste conversion and cleaner products. Different process configurations are possible depending on where the plasma is injected: in the upper part of the reactor close to the waste inlet, at the bottom close to the molten bath, or in a separate chamber to treat the gases leaving the reactor. The higher the presence of hot plasma, the larger the fraction of the waste which is saved from being oxidized, so that it can be converted into syngas. However, an extensive use of plasma implies a significant electricity consumption that, besides being a potential indirect cause of CO_2 emissions, may exceed the energy content of the produced syngas, resulting in a low or even negative net power production of the process.

4.4.2 Solar gasification

By concentrating the diluted sunlight over a small area with the aid of mirrors, it is possible to obtain a dense beam of solar radiative energy that can heat up the carbonaceous waste to the high temperatures necessary for its gasification (Steinfeld et al., 2001). The solar energy input saves part of the feedstock from being burned, so that the process has the potential to be free of combustion byproducts and yield a higher syngas output with respect to conventional gasification. Solar gasifiers, which have been demonstrated capable to operate at high temperatures (>1400 K), can be classified as (i) directly irradiated, where the solid waste is directly exposed to the concentrated radiation, or (ii) indirectly irradiated, where the concentrated solar beam heats up the reactor wall or a heat transfer fluid. Directly irradiated reactors offer efficient heat transfer, but need a transparent window that has to be carefully designed to withstand pressure fluctuations and prevent deposition of particles or condensable compounds on it. Indirectly irradiated reactors eliminate the necessity for a window at the expense of a less efficient heat transfer. The possible reactor configurations can be: packed bed (see Figure 5a), fluidized bed, entrained flow and vortex flow (see Figure 5b), among others. Solar gasification has the potential to be operated also during off-sun periods (i.e. night-time or cloudy days) with the integration of a thermal energy storage unit that can accumulate high-temperature (>900°C) solar heat during the day and release it when required (Ströhle et al., 2017; Gigantino et al., 2019).

4.5 Recycling residues from WtE plants

Treating MSW, IW or landfill waste in WtE plants does not completely solve the problem of waste disposal. Incineration, pyrolysis and gasification can reduce the volume of waste to a great extent, but there are still solid outputs, which can contain significant amounts of pollutants, such as chlorine, dioxins and heavy metals (Chimenos et al., 1999; Gleis et al., 2001; Sorlini et al, 2017).

Several EU states have adopted a critical attitude toward generation and disposal of waste. It is customary for EU countries, such as Belgium, Finland and the Netherlands to treat and recycle MSW bottom ash from WtE plants as aggregates for construction or road-paving (Kahle et al., 2015; Lynn et al., 2017). However, bottom ash does not always fulfill the requirements in terms of content and leaching of pollutants, so that countries such as Austria and Switzerland are still landfilling the ashes. APCR, such as fly ash or boiler ash, are also some of the outputs from WtE plants, which are considered as hazardous waste and need to be disposed of in special landfills, after metal recovery by the FLUWA process. In this regard, gasification and other novel waste treatment technologies could enable the upcycling of the residues after thermal treatment into a new range of eco-friendly construction materials based on inorganic polymers and glass-ceramics. Novel techniques allow to transform inorganic residue from WtE plants into thermal and acoustic isolation materials, such as traditional bricks and tiles (Kriskova et al., 2015; Rabelo Monich et al., 2018; Rincon Romero et al., 2018). An example of such upcycled materials is shown in Figure 6.

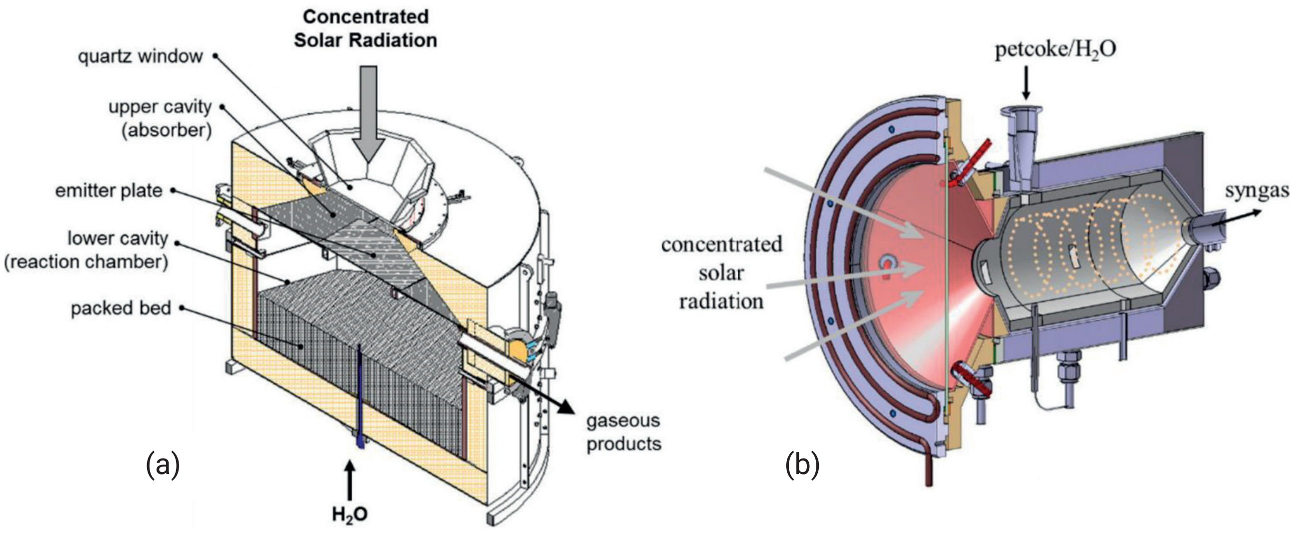

FIGURE 5: Scheme of (a) an indirectly irradiated packed-bed gasifier and of (b) a directly irradiated vortex flow gasifier (Piatkowski et al. 2011b, Z'Graggen et al. 2008).

FIGURE 6: Upcycling of vitrified landfill waste into construction materials (Machiels et al., 2017).

However, the final sink of contaminants in this approach is still unclear.

5. MULTI-CRITERIA ASSESSMENT IN (E)LFM

During the past decade, multi-criteria assessments (MCAs) of LFM projects have become of growing interest to academia, industry, and policymakers. MCAs of LFM aim to account for impacts and risks from an environmental, economic, and societal perspective. Results of such assessments support LFM stakeholders in the decision-making process among the previously described LFM scenarios, i.e. landfill remediation, classical LFM, and ELFM. As described in the previous parts of this study, these scenarios do not refer to a fixed process chain or technologies, but rather show the evolution of a concept to display the major differences and implications of those scenarios.

Most MCAs of LFM projects address environmental impacts and economic feasibility, while societal impacts are typically not addressed (Krook et al., 2018). Environmental impacts are commonly derived from life cycle and risk assessment (Danthurebandara, 2015; Frändegård et al., 2013a, 2013b; Gusca et al., 2015; Jain et al., 2014; Laner et al., 2016), whereas private economic costs and benefits are often determined by the means of the net present value (NPV) (Frändegård et al., 2015; Hermann et al., 2016b; Kieckhäfer et al., 2017; Laner et al., 2019; Winterstetter et al., 2015). Since societal impacts are of a diverse and often complex nature, including welfare changes as well as health risks, no common assessment method for LFM projects exists (Einhäupl et al. 2019a). Moreover, societal impacts are often strongly related to environmental and economic ones, as health risks are usually a consequence of environmental impacts and taxes are accounted for as a private economic cost, but also represent a societal income. Hence, it is often difficult to define clear boundaries between the different dimensions of sustainability in (E)LFM, especially when considering causal relations between different impacts.

Figure 7 displays the sustainability concept as the basis for a holistic multi-criteria assessment in LFM research. The lack of a common and integrated framework, which considers all three sustainability dimensions, shows the complexity of MCAs for LFM projects. While efforts have been made in literature (Hermann et al., 2016a; Pastre et al., 2018) to assess the feasibility of LFM in a holistic manner, challenges, like emerging technologies or long-term impacts of existing landfills, remain with respect to the estimation of the extent of these environmental, economic and societal factors influencing the feasibility of LFM due to varying contextual conditions and related stakeholder perceptions of drivers and barriers.

5.1 From landfill mining to enhanced landfill mining: a conceptual and technological evolution of LFM drivers and barriers

To address the previously mentioned challenges considering future MCA method development and modeling, this study provides a simple synthesis of critical factors that drive or hinder LFM projects as a result of previous sustainability assessments (Table 2). This synthesis discusses motivational drivers and barriers of LFM projects and contrasts the critical factors of the three different LFM scenarios. As previously mentioned, these scenarios represent the evolution of the concept of LFM, which led to changes in perceptions of potential drivers and barriers. For example, while environmental concerns usually drive remediation projects, increasing urbanization and growing resource scarcity have made the reclamation of land and materials important drivers for LFM, still including the potential to reduce surface-, groundwater and soil contamination by excavating the landfill (Marella & Raga, 2014). In

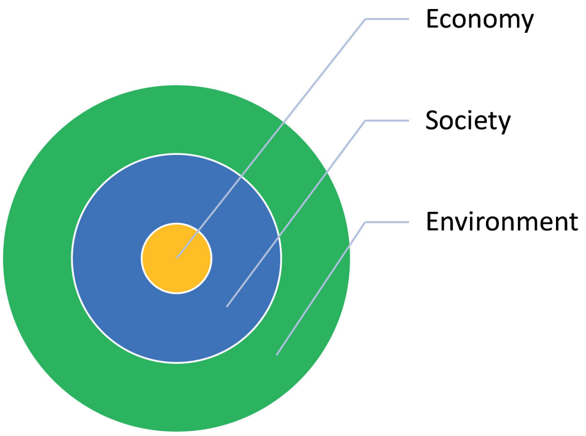

FIGURE 7: The sustainability concept as the basis for multi-criteria assessment in LFM research.

addition, LFM and ELFM have been linked to the avoidance of potential environmental hazard that is due to flooding risk brought by climate change (Laner et al., 2009a; Wille 2018). This could also contribute to the reduction of aftercare and other pollution-related costs. Moreover, technological development could potentially lead to the further valorization of currently re-landfilled waste streams, or their use in lower value applications, leading to the more integrated approach that characterizes the concept of ELFM. Nevertheless, while the mentioned factors represent important drivers for LFM, the excavation and material valorization processes could also lead to additional costs and impacts on every level of sustainability (Hermann et al., 2016a; Marella et al., 2014; Pastre et al., 2018).

The concept of LFM was first introduced in 1953 in Israel (Calderón Márquez et al., 2019; Krook et al., 2012). The aim of that LFM project was to recover materials as fertilizer, while also recovering ferrous and non-ferrous metals (Calderón Márquez et al., 2019). Since then, around 112 projects worldwide have been studied with objectives ranging from environmental protection, over avoidance of closure and post-closure care, the extension of landfill lifetime, land reclamation, to resource recovery, among others (Calderón Márquez et al., 2019). Drivers for the different landfill mining projects have been exhaustively summarized in the study by Calderón Márquez et al., 2019, and are discussed here in light of the evolution of the LFM concept, with particular focus on European projects.

Environmental protection has indeed been the most important driver in LFM (Calderón Márquez et al., 2019; Danthurebandara, 2015; Gusca et al., 2015; Laner et al., 2016; Marella et al., 2014). The need to reduce soil, surface and groundwater contamination has led to an increased interest in remediation strategies. However, given the high costs of remediation processes, new concepts and technologies were developed with the aim to recover valuable resources from landfills, such as combustibles and metals, to compensate the costs and recover materials (Jones et al., 2013; Krook et al., 2012). The concepts of LFM and ELFM, therefore, developed to further increase the resource recovery potential. As mentioned in Van Passel et al., 2013, apart from technological development (technology push), also regulatory- and market- related factors (regulatory push and market pull) determine the economic, societal and environmental performance of LFM projects. These regulatory push factors include legislative changes due to public and environmental pressures, urban development, subsidy schemes or strategic resource independence, among others. On the other hand, market pull factors include increase in material prices and resource competition or rising land prices that can help to facilitate the excavation and processing of the formally buried waste. Market-related barriers for LFM implementation can include quality standards for secondary raw materials, processing capacities of waste incinerators (Johansson et al., 2017b), for example, or a lack of investments due to awareness gaps among stakeholders (Einhäupl et al., 2018). Regulatory barriers mostly derive from legal uncertainty, since it is often unclear if gate fees or taxes that could hinder a project's implementation have to be paid or not (Johansson et al., 2017a). Moreover, public opposition due to environmental uncertainties and the risk of disamenities, i.e. dust, odor, noise, and traffic, can also hinder LFM projects.

During the past years and throughout the studies worldwide, drivers for the mentioned LFM projects have since varied, based on time or local and regional requirements for land-use and landfill void space. Moreover, new landfill regulations, such as the Landfill Directive 1999/EC/31 and similar global regulations on waste disposal, increased the interest in LFM projects to reduce risks of contamination and the related costs, as well as to comply with closure and post-closure requirements (Calderón Márquez et al., 2019; Laner et al., 2016). Today, landfills predating the 1999 Landfill Directive are commonly referred to as ”dumpsites”. As most dumpsites are lacking up-to-date environmental protection measures, classic remediation has usually motivated the excavation of such landfills.

While regulation can push project implementation, as well as hinder it, it is important to take a closer look at the regulatory situation of (E)LFM today. In general, the so-called EU Landfill Directive defines the legal framework for the design, management and closure of landfills (Council Directive, 1999). The so-called EU Waste Directive defines the regulations for waste treatment and safety issues when treating hazardous waste materials, for example (Council Directive, 2008). Since the request for an ELFM amendment to the Landfill Directive was rejected by the EU Commission in 2018, no specific regulations for (E)LFM exist (Jones et al., 2018), adding to the legal uncertainty. However, according to the EU Commission and a legal report from Austria, no current regulations prohibit (E)LFM operations, even at an industrial scale and scope (Eisenberger, 2015; Jones et al., 2018). Nonetheless, the lack of overarching European legislation leaves member states with a variety of options to deal with (E)LFM and gives little room to address common challenges for its implementation (Einhäupl et a., 2019b).

Table 2 summarizes the drivers for LFM projects and their evolution from the remediation concepts to enhanced landfill mining. As shown in Table 2, the goal of ELFM compared to LFM is to maximize the recovery of resources while complying with all other objectives (environmental protection, societal benefits, etc.). Hence, to minimize the re-disposal of excavated fractions is an important focus of ELFM projects.

5.2 Critical factors of LFM projects

Increasing environmental and societal pressures and higher resource recovery targets have led to increasing challenges related to the waste processing technologies and, therefore, to the quality and quantity of the materials and energy recuperation. Economic, environmental and societal assessments of LFM and ELFM projects have highlighted the influence of critical factors in the feasibility and potential benefits of such projects. For example, while potential economic benefits could mainly derive from land reclamation, and material and energy valorization (Hermann et al., 2016b; Krook & Baas, 2013), potential costs are related to the excavation and processing of the different waste fractions (Hermann et al., 2016b). These costs

TABLE 2: Drivers and barriers throughout the evolution of the LFM concepts.

	Landfill remediation	Landfill mining	Criteria on leaching?
Drivers	• Environmental protection (remediation)	• Environmental protection (remediation) and • risk mitigation • Legislative changes • Cost reduction through resource recovery • Extension of useful landfill lifetime • Mitigation of closure and post-closure after-care • Urban development • Flooding risk	LFM drivers with the addition of: • Resource recovery (maximization) • Innovative landfill management concept: integrated valorization routes • Minimization of re-landfilling of waste • Resource independence • Increasing resource scarcity
Barriers	• Remediation costs	• Low market prices for primary and secondary raw materials • Relatively high processing costs	• Public opposition • Quality standards • Legal uncertainty • Taxes and fees • Technological challenges

are highly dependent on the waste composition and quality, as well as technology choices. Implied environmental impacts again can cause potential societal impacts that can lead to public opposition, for example.

In general, technology availabilities and efficiencies for processing landfilled waste are still uncertain and under current investigation. These technological uncertainties make it difficult to assess LFM projects, as potentially related costs, risks and impacts could outweigh the potential benefits (Hermann et al., 2016b; Krook et al., 2012).

In the relevant literature, critical factors are often discussed based on their influence on the economic, environmental or societal performance of the LFM projects (Danthurebandara, 2015; Frändegård et al., 2013b; Gusca et al., 2015; Hermann et al., 2014; Laner et al., 2016). However, most factors have implications for two or all sustainability dimensions. For example, environmental protection, which addresses the need to minimize soil, surface and groundwater contamination, has mostly been discussed as an environmental driver. Nonetheless, this has economic and societal implications in the reduction of pollution-related costs or of health risks to local communities. The recovery of materials and their marketability has potential environmental and economic benefits from the avoided production of primary materials, and the revenues from the secondary raw materials. From a societal perspective processing and recycling of waste could lead to job creation, avoid post-closure costs and risks, or increase property values. Given the interconnection of the factors between the three sustainability dimensions, a few studies have divided the critical factors affecting the performance and feasibility of LFM projects according to the level of influence (Laner et al., 2016; Winterstetter, 2018; Winterstetter et al., 2018). In particular, site-, project-, and system-level factors have been identified, which are summarized in Table 3.

At a site-level, waste composition is one of the main critical factors in LFM projects and multi-criteria assessments, and strictly related to the specific landfill. Waste composition influences the emission potential of the landfill and, therefore, the environmental impacts, pollution related costs and remediation requirements. It also greatly affects the resource recovery potential of LFM and the valorization routes suitable for the specific case (García López et al., 2019; Hernández Parrodi et al., 2018b; Quaghebeur et al., 2013). Moreover, disamenities like dust and odor are partly dependent on the waste composition. Quality and quantity of materials define the choice of technologies and their efficiencies, which have proven to be critical factors in previous economic and environmental studies of LFM (Danthurebandara, 2015; Frändegård et al., 2013a; Gusca et al., 2015; Laner et al., 2016). In environmental and economic assessments, given the importance of environmental protection as one of the main drivers, the reference case is also of great importance. It represents the importance of leaving the landfill as it is, with environmental, societal and economic consequences. These are related to the landfill emission potential which can last for centuries after landfill closure (Doka et al., 2005; Laner et al., 2009b), and which are respectively related to the waste composition and its degradability, as well as landfill design and management (Laner, 2011a).

At a project-level, technology choices and their efficiencies greatly affect the performance of LFM. In particular, technology choices for WtM and WtE, combined with the background energy system and the waste quality, could be decisive in potential applications of LFM (Frändegård et al., 2013a; Gusca et al., 2015; Laner et al., 2016). In fact, the overall aim is to outweigh the costs and impacts related to the reference case with the processing and recovery of resources. Excavation, separation and sorting technologies could have high environmental and economic impacts, also in relation to the quantity and quality of the materials recovered. On-site and off-site processing options also affect the performance, as transportation distances have been identified as critical factors (Frändegård et al., 2013a; Gusca et al., 2015). Given the high amounts of waste that LFM projects could address, logistics also becomes an important factor. Storage and processing capacities and equipment are also crucial for the design of valorization routes, the quality and quantity of recoverable materials (Kieckhäfer et al., 2017). In addition, the choice of project motivation, i.e. the main driver, in terms of land recovery or void space recovery has critical influence on the performance of an LFM project. Land recovery means external re-landfilling of fine fractions, while void space recovery means internal re-landfilling. With the large share of fine fractions in the landfill waste composition (Hernández Parrodi et al., 2018a), its subsequent choice of management is particularly important (Laner et al., 2019).

System-level factors are those which cannot be ad-

TABLE 3: Selection of critical factors for (E)LFM implementation at the level of impact.

Critical factors		
Site-specific	**Project-level**	**System-level**
• Waste composition: quantity and quality of resources for recovery • Reference case	• Technology choices and efficiencies: - Excavation, separation, and sorting (mobile, stationary and advanced, etc.) - WtE treatment: type and efficiency, energy carriers • Quality of the materials recovered and marketability • Logistics • Energy and processing costs • Investment and operating costs, costs for external treatment and disposal • Land or void space recovery • Avoided impacts	• Background energy system • Primary material production system • Transportation: requirements and distances • Financial effects • Materials and energy prices • Legal, institutional, organizational, and societal structures: - Policy support - Community engagement

dressed for each case specifically, but that influence the environmental, economic and societal performances as they refer to country-specific, European-, or even global structures. These include legal, institutional, organizational and societal structures. In particular, the background energy system influences the environmental impacts based on the energy production mix of the country of implementation of the project. Materials and energy prices, and their variation in time affect the revenues of materials and energy recovery, also in relation to primary raw materials. The marketability of valorized WtE residues is also uncertain, as different studies have assumed different prices to no market at all (Danthurebandara et al., 2015; Winterstetter et al., 2015). Similarly, the value of recovered land and landfill void space depends on the existing market conditions, but also influenced by site-specific factors like location: whether a landfill is situated nearby a residential, industrial or natural areas (Marella et al., 2014; Van Passel et al., 2013).

Societal aspects are therefore becoming of increasing interest in the multi-criteria assessment of LFM, and have been mentioned throughout the relevant literature. When assessed, however, commonly interviews and ranking systems are used (Hermann et al., 2016b; Pastre et al., 2018) as well as monetization techniques (Marella et al., 2014; Winterstetter et al., 2018). Consequently, considerable subjectivity resonates with the assessment of societal factors, and various societal effects become entangled. This again leaves decision-makers having to deal with major uncertainties when evaluating societal risks and benefits, such as safety issues, health implications through groundwater contamination (Krook et al., 2012), disamenities (Einhäupl et al., 2018), welfare changes (Damigos et al., 2016) and so on. Before evaluating these risks and benefits it is important to carefully analyze societal drivers and barriers for LFM implementation to better understand the origins and mechanisms behind the impacts.

When integrating economic, environmental and societal impacts and perspectives into LFM multi-criteria assessment, several issues have to be addressed. LFM multi-criteria assessment has to deal with intra- and inter-dimensional trade-offs and conflicts. For example, taxes for re-landfilling excavated waste is a private economic cost and could, thus, hinder a project's implementation. On the other hand, these tax revenues are also a societal benefit. Moreover, different stakeholders are affected by various societal and environmental impacts. Emissions like particular matter coming from LFM operations affect neighboring communities, for example, while avoided impacts are often manifested in other locations or at a global level. To deal with these issues more research is needed. Specifically, the most important influencing factors on societal risks and benefits have to be identified and their interaction with private economic and environmental aspects analyzed.

6. CONCLUSIONS

This review article has extensively highlighted the current scenarios for landfill management and potential scenarios for the combined valorisation of waste, as both materials (WtM) and energy (WtE).

Landfills represent a source of hazards to human health and the environment. Moreover, the long-term potential emissions of landfills and the risk of failure of the containment systems, increase the need for aftercare activities and their related costs. In a context of lack of land surface and primary resources, landfills also represent a source of feedstock that could be recovered to answer the increasing demand for raw materials. LFM aims at addressing the potential to recover waste from landfills, while reducing the long-term impacts of landfills by remediating the sites.

Different scenarios can be considered which address LFM to different extents. Overall, the choice of scenario depends on technical, as well as economic, environmental and societal aspects. New technologies are under research to increase the recovery potential of waste materials, such as MSW and excavated waste from landfills. One of the main factors that influences the technical feasibility and efficiency of the recovery processes, is the quality of landfilled waste, since its heterogeneity, agglomeration, degradation and contamination could hinder the potential for material and energy recovery. Therefore, material composition and physicochemical properties of the waste disposed of in a landfill site are some of the preliminary and most important information to be gathered in order to assess the economic, technical and environmental feasibility of the project. Geophysical methods could be used to determine the subsurface structures and landfilled waste characteristics in a rough manner without the need of an invasive exploration, as well as to identify the most interesting area, in terms of depth, water content and presence of certain materials, before carrying out the extraction of landfilled waste. This could greatly reduce the exploration costs and be useful to develop a procedure to either discard or select the most appropriate sites for (E)LFM.

The recovery of material and energy from landfilled waste can be achieved through the implementation of relatively simple separation methods, such as particle size classification, ferrous and non-ferrous metal separation, density classification and sensor-based sorting, coupled with thermochemical valorization technologies and residues upcycling techniques. Gasification, among other novel waste treatment technologies, could enable the upcycling of the residues after thermal treatment into a new range of eco-friendly construction materials based on inorganic polymers and glass-ceramics, which allow to transform inorganic residue from WtE plants into thermal and acoustic isolation materials, such as traditional bricks and tiles.

As for the technical aspects, the multi-criteria assessment of ELFM is also influenced by the same waste- and technology related factors. These, together with site-specific conditions, market and regulatory aspects, influence the environmental, economic and societal impacts of this kind of projects. Intra- and interdimensional conflicts should be identified and taken into account for a broader assessment. The most influencing factors need to be considered at different levels to cover landfill emissions and societal impacts (site-level), include technology choices (project-level) and take into account the regulatory context (system-level) and background system.

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3 FINE FRACTIONS FROM LANDFILL MINING

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Annotation on my personal contribution to this scientific article:

I thoroughly reviewed previous LFM investigations on the fine fractions and collected and summarized the most relevant information. I wrote most of the article in consultation with Daniel Höllen and Roland Pomberger. All 3 authors of the article were involved in its review and I conducted the revision.

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CHARACTERIZATION OF FINE FRACTIONS FROM LANDFILL MINING: A REVIEW OF PREVIOUS INVESTIGATIONS

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ABSTRACT

Several landfill mining (LFM) studies have been carried out in recent years all around the world. From these studies qualitative and quantitative information regarding the composition and characteristics of the different fractions excavated from landfills has been obtained. This information comprises data from various landfill sites around the globe from which useful correlations for future LFM projects can be identified. Of particular interest to this paper is the information regarding the fine fractions, which represent to this day a crucial obstacle in the implementation of LFM and enhanced landfill mining (ELFM). The fine fractions make up a considerable portion of the total amount of waste disposed of in landfills. Depending on the particle size chosen as upper limit to define the fines fraction, the portion of this fraction can be as high as 40-80 wt.% of the total excavated waste. These fractions consist of decomposed organic substances, e.g. humic substances, partly weathered mineral waste, e.g. sand, brick fragments, concrete, but also of fine metal particles, especially non-ferrous metals, and still a significant amount of plastics, paper and other calorific fractions. However, although calorific fractions might be used for energy recovery and inorganic fractions for material (especially metal) recovery, current LFM studies are discarding the fine fraction due to lacking or too expensive processing routes. Therefore, it is of critical interest to LFM and ELFM projects to reduce the particle size down to which the excavated material can be processed. This paper, which was elaborated within the framework of the EU Training Network for Resource Recovery through Enhanced Landfill Mining – NEW-MINE, aims to review the obtained data from different LFM studies from municipal solid waste (MSW) landfills, concerning the fines fraction, in order to identify key aspects to be taken into consideration while designing the processing approach in future LFM and ELFM investigations.

1. INTRODUCTION

Since its commencement, in 1953 at the Hirya landfill in Israel (Savage, Golueke, & Von Stein, 1993), the focus of LFM has been evolving, incorporating different drivers and objectives to its original purpose over the years. To this day, some common drivers of LFM projects have been: material recovery (recyclable and reusable materials), land reclamation, landfill capacity regain, pollution mitigation, landfill remediation, removal of deposits obstructing urban development, production of alternative fuels, aftercare and closure costs reduction, enabling the operation of regional MSW incinerators at full capacity, reuse of already available landfill infrastructure, simplification of the permitting process, among others (Hull, Krogmann, & Strom, 2005; Krook, Svensson, & Eklund, 2012).

Moreover, a holistic concept, ELFM, has been developed during this decade. This approach envisages the combined and integrated waste valorization of old and future waste deposits as both materials (Waste-to-Material, WtM) and energy (Waste-to-Energy, WtE); while respecting most stringent ecological and social criteria (Jones, Geysen, Rossy, & Bienge, 2010).

Since landfills were for decades the sole disposal solution for all types of waste with any segregation, they represent a heterogeneous source of materials (Kaartinen, Sormunen, & Rintala, 2013). Previous investigations made by Krook et al., 2012; Cossu, Motzo, & Laudadio, 1995, Kaartinen et al., 2013; Prechthai, Padmasri, & Visvanathan, 2008; Quaghebeur et al., 2013; Zhao, Song, Huang, Song, & Li, 2007 report that landfill-mined waste normally consists of 20-30 wt.% combustible materials, 50-60 wt.% fine-grained degraded matter, 10 wt.% inert materials and a small percentage of metals. For further references predating year 2011, a broad worldwide overview of over 60 LFM projects

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and the rough composition of landfilled waste from over 20 landfill dismantling and exploratory drilling projects can be consulted in the work made by Bockreis & Knapp, 2011.

A more detailed material composition (Van Vossen & Prent, 2011), obtained from information found in literature of 60 landfill mining projects, plus the outcomes of most recent investigations (after year 2011) are presented in Table 1.

In this information (Table 1) it can be noticed that the fine fractions (referred sometimes as “soil”, “soil-like” or “soil-type” fractions, due to their appearance, organic matter and mineral contents and relatively homogeneous composition compared to the coarser fractions) are commonly to a great extent the largest fraction of the whole excavated amount in a LFM project. These fractions typically contain mainly degraded garden and food materials (Quaghebeur et al., 2013). This degradation process can be compared to the natural humification process during soil formation. Since the US EPA reported that around 75% of the LFM material corresponds to mineral landfill liners and degraded organic waste (Landfill Reclamation, 1997), a comparison

TABLE 1: Material composition of excavated waste from previous LFM investigations.

Parameter	Van Vossen and Prent, 2011 (various countries)	Jani et al., 2016 (Högbytorp, Sweden)	Kaartinen et al., 2013 (Kuopio, Finland)	Bhatnagar et al., 2017 (Kudjape, Estonia)	Wolfsberger et al., 2015 (Lower Austria, Austria)	Quaghebeur et al., 2013 (REMO, Belgium)
Type of waste disposed of	Various	MSW + C&D	MSW	MSW	MSW	MSW
Age of waste [a]	Various	5	5 - 10	10	13 - 20	14 - 29
Fraction(s) considered	All	10 - 40 mm	All	All	All	All
Average moisture content	-	-	-	-	29.0 - 55.0%	53.0 - 68.0%
Fines / Sorting residue / Soil-type material	54.8%	27.3%	50.0 - 54.0%	28.7%	47.0%	44.0 ± 12.0%
Stones	2.5%	28.1%	-	17.5%	-	-
Minerals / Inert	5.8%	-	-	-	6.0%	10.0 ± 6.0%
C&D	9.0%	-	-	-	-	-
Limestone	-	4.8%	-	-	-	-
Asphalt	-	3.2%	-	-	-	-
Glass / Ceramics	1.1%	5.6%	-	4.6%	1.0%	1.3 ± 0.8%
Plastics	4.7%	-	23.0%	22.4%	18.0%	17.0 ± 10.0%
Soft plastics	-	0.7%	-	-	-	-
Other plastic / Composites	-	6.8%	-	-	4.0%	-
Organic / Kitchen waste	5.3%	-	-	-	-	-
Paper & cardboard / PPC	5.3%	-	4.0 - 8.0%	5.1%	3.0%	7.5 ± 6.0%
Paper	-	4.5%	-	-	-	-
Wood	3.5%	15.2%	6.0 - 7.0%	4.7%	-	6.7 ± 5.0%
Textiles	1.6%	2.7%	7.0%	-	6.0%	6.8 ± 6.0%
Leather	1.6%	-	-	-	-	-
Rubber	-	0.2%	-	-	-	-
Wood, leather and rubber	-	-	-	-	9.0%	-
Total metals	2.0%	-	3.0 - 4.0%	3.1%	5.0%	2.8 ± 1.0%
Fe metals	-	0.5%	-	-	-	-
Non-Fe metals	-	0.5%	-	-	-	-
Other / Rest	2.6%	-	2.0%	13.4%	1.0%	-
Non-MSW	0.3%	-	-	-	-	-
Notes:	*Information organized according to age of waste* *Totals may not add exactly 100% due to figures´ rounding* *Figures have weight and wet basis* *MSW - Municipal solid waste* *C&D - Construction and demolition waste* *PPC - Paper, paperboard and cardboard*					

to natural soils which also contain fine-grained mineral and organic materials can be drawn. However, the different genesis of the fine fractions in landfills and of soils, and the lack of separation of the fine fractions from other materials in the landfill, do not allow addressing the fine fractions from landfills as soils.

Fine fractions (frequently defined as material with a particle size < 60 mm to < 10 mm) account for 40-80 wt.% of the mined material in previous studies (Hogland, 2002; Masi, Caniani, Grieco, Lioi, & Mancini, 2014; Kaartinen et al., 2013; Kurian, Esakku, Palanivelu, & Selvam, 2003; Rettenberger, 2009; Hull et al., 2005; Mönkäre, Palmroth, & Rintala, 2016; Quaghebeur et al., 2013; Maul & Pretz, 2016; Van Vossen & Prent, 2011; Wiemer, Bartsch, & Schmeisky, 2009; Wolfsberger et al., 2015). Therefore, regardless of the particle size used to define the fine fractions, its quantity will always be an important factor to be considered in LFM and ELFM projects.

The main purpose of the present review is to gather information regarding the fine fractions of previous LFM investigations, in order to identify their composition and properties, so that the possibility of material and energy recovery from these fractions can be assessed in forthcoming research, as well as to identify key aspects to be taken into account while designing the processing approach in future LFM and ELFM investigations.

2. MATERIALS AND METHODS

The present study comprises a review of several previous LFM investigations found in scientific literature. The main focus of this review paper is on the material characterization of the fine fractions. The scope envisages scientific papers published in international peer-reviewed journals, as well as a minor amount of other review papers and international conference proceedings, books, guidelines, standards and legislation.

3. REVIEW AND DISCUSSION

There have been plenty of LFM projects and investigations carried out up to now; nevertheless, not much attention has been paid to the fine fractions in terms of their potential for material recovery, alternative fuels production and possible alternative uses (e.g. as cover layer in operating landfills, as filling material for leveling purposes or the construction of embankments, as soil improver for growing nonedible crops, etc.). In most LFM projects recycling has been restricted to the coarse fractions, while the fine fractions have been re-directed to the landfill with poor or no treatment beforehand, mainly due to technical and economic challenges, despite their recovery potential (Bhatnagar et al., 2017; Münnich, Fricke, Wanka, & Zeiner, 2013).

According to previous investigations (Kaartinen et al., 2013; Mönkäre et al., 2016; Wolfsberger et al., 2015) the amount of fines to be obtained in a LFM project mostly depends on the excavation procedure, the age of the waste and the selected cut-off diameter to define a certain particle size as upper limit for the fine fractions. For example: (i) the implementation of borehole sampling via drilling activities can increase the amount of fine fractions in the samples, (ii) the amount of fine fractions has been found to raise with age in some investigations and (iii) the amount of material passing the screen tends to increase with the increase in size of the cut-off diameter of the screen. However, these factors might be correlated with one another and each of them can increase or decrease the amount of fine fractions by itself. Therefore, the specific setup employed in a particular LFM project is to be analyzed in a single-case base, in order to determine the overall effect of these factors on the total amount of fine fractions to be obtained.

Additionally, the characteristics of the fine fractions of landfill-mined material can be influenced by the chosen processing, e. g. sieve size affects utilization and disposal methods of the sieved materials, as it has been observed that the methane potential rises with the increase of particle size (Mönkäre et al., 2016). Moreover, the amount of fine fractions increases with time due to the decomposition processes (Jani et al., 2016). Long disposal time leads to degradation processes of the organic matter, which leads to a higher amount of fines (Maul & Pretz, 2016).

Because of the lack of economic value, the characterization properties of the fine fractions have not been thoroughly investigated (Mönkäre et al., 2016). Nonetheless, in order to evaluate the specific recycling potential of a landfill, adequate and proper quantitative and qualitative characterizations of the disposed waste are to be performed (Prechthai et al., 2008).

It is important to point out that much care needs to be taken when comparing information between different investigations directly, since there are many factors, such as; characterization conditions and procedures, laboratory analyses and followed standards, age of the waste material, defined particle size for the fines fraction, among others, that might play an important role during their execution and may differ significantly from investigation to investigation. The implementation of different approaches for the material characterization of waste remains to be one of the crucial challenges for the elaboration of comparable and accurate compiled studies.

3.1 Material composition

In this paper, material composition refers to the kind of material, e.g. “plastic” or “textiles”, whereas chemical composition refers to the elemental composition and mineralogical composition to the phase composition. On the basis of the result of previous studies on the material composition of the fine fractions, of excavated waste from landfill, some tendencies can be recognized. Table 2 shows a compilation of these studies and their reported results. Some clear trends that can be noticed, apart from the already stated clear dominance of the amount of fines over the total, are the considerable amounts, in some cases, of inert materials (mainly stones and glass), plastics, textiles, paper and metals present in these fractions. This information allows grouping the sub-fractions that constitute the fine fractions in to major constituents, which are degraded organic and mineral materials, and minor constituents, which are plastics, textiles, metals paper and

TABLE 2: Material composition of excavated fine fractions from previous LFM investigations.

Parameter	(Filborna, Sweden) in Kurian et al., 2003	Wolfsberger et al., 2015 (Lower Austria, Austria)	Hull et al., 2005 (BCRRC, USA)	Kurian et al., 2003 (Perungudi, India)	Kurian et al., 2003 (Kodungaiyur, India)	(Deonar, India) in Kurian et al., 2003
Type of waste disposed of	MSW	MSW	MSW + C&D + IW	MSW	MSW	MSW
Age of waste [a]	-	13 - 20	1 - 11	0 - 10	10	-
Particle size [mm]	< 40	< 40	< 25.4	< 20	< 20	< 8
Amount of fines from the whole	65.7%	68.0%	≥ 50%	58.9%	32.3%	34.6%
Sorting residue	-	65.6%	-	-	-	-
Stones	19.0%	-	-	18.5%	28.3%	31.5%
Minerals / Inert	-	6.6%	-	-	-	-
Glass	0.5%	1.4%	-	0.8%	0.4%	-
Wood	-	-	8.5 - 11.7%	-	-	-
Wood, leather, rubber	15.7%	5.9%	-	26.1%	1.0%	1.2%
Textiles / Rubber	4.5%	1.9%	5.4 - 6.8%	2.3%	0.6%	-
Plastics	18.1%	11.6%	10.5 - 19.5%	11.0%	1.9%	1.5%
Composites	-	1.0%	-	-	-	-
PPC	-	3.0%	-	-	-	-
Paper	-	-	6.8 - 14.4%	-	-	-
Cardboard	-	-	4.6 - 14.9%	-	-	-
Total metals	7.9%	1.9%	-	0.2%	0.1%	0.4%
Fe metals	-	-	5.5 - 12.6%	-	-	-
Others	-	1.1%	-	-	-	-
Problematic substances	-	0.1%	-	-	-	-
Notes:	*Information organized according to particle size* *Totals may not add exactly 100% due to figures´ rounding* *Figures have weight and wet basis* *MSW - Municipal solid waste* *C&D - Construction and demolition waste* *IW - Industrial waste* *PPC - Paper, paperboard and cardboard*					

cardboard, among others. Below, particular tendencies and aspects that have been found in former investigations are discussed.

The fine fractions have been found aesthetically unpleasant due to the presence of non-soil materials, such as plastic and paper flakes and broken glass (Hull et al., 2005). Zhao et al., 2007 reported that the fine fractions showed similarities to black soil and suggested, therefore, a use for green construction, organic fertilizer or as bioreactor media for biological treatment of leachate. Bhatnagar et al., 2017 identified the fraction < 40 mm as composed of 22 wt.% inert materials (glass and stones), 5.4 wt.% biodegradables (paper and wood), 5 wt.% combustibles (mix of plastic textile and rubber), 1 wt.% metals (Fe, Cu and Al) and a larger amount of non-identified material. An amount of about 20 wt.% DM of the fraction < 25.4 mm was reported by Hull et al., 2005 to be accounted for the sum of metal, plastic, glass, textile/rubber/leather and stone/brick/concrete materials.

According to the findings of Prechthai et al., 2008 and Masi et al., 2014, the fractions < 25 mm and < 10 mm, respectively, were mainly composed of organic matter and fine-grained mineral matter, pieces of wood, metals, glass and plastics. The fraction 0.425-6.3 mm was mainly constituted by degraded organic matter mixed with broken glass and ceramics, whereas the fraction < 0.425 mm was composed mainly of mineral particles (Jain, Kim, & Townsend, 2005). A soil-like mixture of minerals and organic matter was the most abundant material in the fraction < 20 mm identified by manual sorting reported by Kaartinen et al., 2013; this fraction was particularly dominant within the fraction < 4 mm.

The high content of fine-grained aggregates of mineral and organic particles in the aged MSW is likely the result of the daily covering soil (Chen, Guan, Liu, Zhou, & Zhu, 2010) and the humification of organic matter in fresh MSW. Organic waste normally degrades and cannot be identified after some years of being landfilled (Quaghebeur et al., 2013), since the material is gradually transformed into humus. Humus is the stable state reached by organic matter after being degraded down to the point where organic matter resists further degradation and constitutes one of the main components of soil, together with liquids, gases, minerals and living microorganisms (Stevenson, 1994).

Prechthai et al., 2008 found no significant variation in waste-type composition of waste among different sampling locations within one landfill. However, he reported variations in the composition of the fine fractions along the vertical profile, suggesting a variation depending on the degree of biodegradation of waste over time in the dumpsite. Changes regarding the content of individual fractions over time were also observed by Chen et al., 2010; Hull et al., 2005; Kaartinen et al., 2013; Quaghebeur et al., 2013; Sormunen, Laurila, & Rintala, 2013, where the mass fractions of paper and cardboard, textiles and wood were lower in older wastes. This was also the case for Jain et al., 2005, where the lower percentage of paper found in samples of an older part of the landfill than in the more recent one suggest the decomposition of paper over time. The quantity of paper-cardboard in excavated waste seems to be a useful parameter regarding the stabilization state of the material that can be easily determined on site (Francois, Feuillade, Skhiri, Lagier, & Matejka, 2006).

Further data on the material composition of the fine fractions shows that the amount of degradable components decreased over time, while the amount of degraded components increased up to 60 wt.% (Francois et al., 2006). Such changes can be also attributed to the composition differences of the landfilled waste due to waste management systems, legislation, changes in the consumption and production trends during the landfilling lapse (Quaghebeur et al., 2013; Spooren, Nielsen, Quaghebeur, & Tielemans, 2012).

The data on the amount of plastic, metal, glass and inert materials did not present a significant variation in time, matching with the expected behavior for slow- or non-biodegradable components (Francois et al., 2006). Plastics recovered from landfills show similar properties to those of plastics from MSW and other secondary plastics (Maul & Pretz, 2016).

Therefore, it can be concluded from previous studies that the amount of biodegradable materials, from the initial quantity, in landfill sites tends to decrease with time, while the amount of slow- and non-biodegradable materials tends to remain without high variations.

According to Wolfsberger et al., 2015 the amount of recyclables and materials for energy recovery in the fine fractions (< 40 mm) was significantly lower than in the coarse fractions, identified around 33 wt.% for the fine fraction. This value, despite being lower than for the coarse fractions, represents an interesting amount of material due to the fact that the fine fractions make up most of the excavated material. For instance, according to Bhatnagar et al., 2017, it would be possible to obtain 23% revenue, with respect to the total income from material recovery, via individual materials from the fraction < 40 mm.

Quaghebeur et al., 2013 reports that for certain waste fractions (i.e. metals, plastics, glass/ceramics, stones and textile) the amount found in the excavated material was comparable to the amount originally present in the waste when initially landfilled. Therefore, records with regard to the composition of fresh waste sent to a landfill over time can be a good source of information to estimate the composition of the disposed material at the site; with exception of biologically degradable materials, especially biowaste, followed by paper and paperboard, which degrade over time (Quaghebeur et al., 2013).

The previous data suggest that the fine fractions might result interesting as source of potentially recoverable materials as metals, plastics and soil-like material, as well as a source of inert materials like sand, glass and ceramics. However, when the quality of paper and cardboard, plastics, textiles and wood (calorific fractions in general) recovered from a landfill is too low or when concentrations of specific compounds, whose amounts are restricted in certain recycling routes are exceeded, waste-to-energy could be the most suitable valorization path (Quaghebeur et al., 2013). Nevertheless, there are also limit values for certain pollutants that apply to WtE and need to be taken into account. For example, an Austrian investigation accounts for a case in which several calorific fractions from LFM material did not meet the limit values applicable in Austria (Wolfsberger et al., 2015). For instance, washing of plastics from LFM reduced the contents of most heavy metals, but not of antimony (Sb) which was incorporated into the polymer (Liebetegger, 2015).

3.2 Particle size distribution

Table 3 gives an overview of the results on the particle size distribution of different studies: for most of the studies, the biggest amount of material belongs to the fine fractions, followed by the coarse fractions and the intermediate fractions. Logically, their amounts will depend mainly on the set particle size for the sieving process, but, however, most of the reviewed previous investigations have shown a consistent dominance of fractions < 40 mm upon the coarser fractions. Information of this kind is difficult to compare, since same particle sizes for the sieving of the excavated material are hardly used in different investigations.

A study on the physico-chemical characteristics of landfilled municipal solid waste of various ages (3, 8, 20 and 30 years old) at four different sites realized by Francois et al., 2006, shows that the particle size distribution of the waste (considering materials ≥ 100 mm as coarse fraction, materials < 100 mm but >= 20 mm as middle fraction and materials < 20 mm as fine fraction) changes from predominantly coarse fraction (approx. 50 wt.%) for 3 years old waste to mainly fine and middle fractions for 30 years old waste (approx. 46 wt.% and 40 wt.%, respectively). The data obtained from the time in between, 8 and 20 years old, show a clear gradual amount reduction of the coarse fraction, as well as a clear gradual amount increase of the fine fraction. The data for the middle fraction shows some fluctuation over time, as it would be logically expected.

Landfill mining tests carried out at a MSW landfill in Sweden by (Hogland, Marques, & Nimmermark, 2004) revealed that about 70-80 wt.% of the fraction < 18 mm (17-22 years old waste) in all excavated depths was within the size range 10-1 mm.

Figure 1 depicts the particle size distribution within the fine fractions of additional studies. Most of these studies present similar results to those of Hogland et al., 2004, where the majority of the fine fractions of excavated land-

TABLE 3: Particle size distribution of excavated waste from previous LFM investigations.

Parameter		Prechthai et al., 2008 (Nonthaburi, Thailand)	Jani et al., 2016 (Högbytorp, Sweden)	Jain et al., 2005 (ACSWL, USA)	Mönkäre et al., 2016 (Kuopio, Finland)	Kaartinen et al., 2013 (Kuopio, Finland)	Hull et al., 2005 (BCRRC, USA)	Zhao et al., 2007 (Shanghai, China)	Hogland et al., 2004 (Maasalycke, Sweden)	Quaghebeur et al., 2013 (REMO, Belgium)	Mönkäre et al., 2016 (Lohja, Finland)	Masi et al., 2014 (Lavello, Italy)	Masi et al., 2014 (Lavello, Italy)
Type of waste disposed of		MSW	MSW + C&D	MSW	MSW	MSW	MSW + C&D + IW	MSW	MSW	MSW	MSW + C&D + soil	MSW	MSW
Age of waste [a]		3 - 5	5	3 - 8	1 - 10	5 - 10	1 - 11	8 - 10	17 - 22	14 - 29	24 - 40	30 - 60	30 - 60
Particle size	> 100 mm	-	-	-	-	31.0 - 34.0%	-	-	-	-	-	-	-
	> 50 mm	69.0%	-	-	-	-	-	-	48.2 - 59.2%	-	-	-	-
	> 40 mm	-	24.0%	-	-	-	-	25.5 - 70.6%	-	-	-	-	-
	> 6.3 mm	-	-	40.9%	-	-	-	-	-	-	-	-	-
	40 - 100 mm	-	-	-	-	16.0 - 17.0%	-	-	-	-	-	-	-
	25 - 50 mm	13.0%	-	-	-	-	-	-	-	-	-	-	-
	18 - 50 mm	-	-	-	-	-	-	-	21.8 - 31.4%	-	-	-	-
	20 - 40 mm	-	-	-	-	6.0%	-	-	-	-	-	-	-
	15 - 40 mm	-	-	-	-	-	-	14.9 - 32.6%	-	-	-	-	-
	10 - 40 mm	-	38.0%	-	-	-	-	-	-	-	-	-	-
	0.425 - 6.3 mm	-	-	14.5%	-	-	-	-	-	-	-	-	-
	< 25.4 mm	-	-	-	-	-	50.0 - 52.0%	-	-	-	-	-	-
	< 25 mm	18.0%	-	-	-	-	-	-	-	-	-	-	-
	< 20 mm	-	-	-	38.0 - 53.9%	43.0 - 47.0%	-	-	-	-	39.8 - 73.6%	-	-
	< 18 mm	-	-	-	-	-	-	-	14.8 - 24.7%	-	-	-	-
	< 15 mm	-	-	-	-	-	-	12.8 - 45.3%	-	-	-	-	-
	< 10 mm	-	38.0%	-	-	-	-	-	-	44.0 ± 12.0%	-	70.4%	-
	< 4 mm	-	-	-	-	-	-	-	-	-	-	-	63.6%
	< 0.425 mm	-	-	44.6%	-	-	-	-	-	-	-	-	-
Notes:		*Information organized according to age of waste* *Figures have weight basis* *MSW - Municipal solid waste* *C&D - Construction and demolition waste* *IW - Industrial waste*											

fill MSW / MSW + C&D / MSW + C&D + IW / MSW + C&D + soil with various waste ages were composed of a particle size over 1 mm.

On the other hand, according to Jani et al., 2016 the fraction < 10 mm represented 38 wt.% of the total excavated material (5 years old MSW + C&D material) and were composed mainly of soil-like material and minerals; from which 98 wt.% were smaller than 4 mm and 80 wt.% were smaller than 2 mm.

Previous LFM studies have similar results. For instance, Mönkäre et al., 2016 reported that about 78-81 wt.% of the fraction < 20 mm was smaller than 11.2 mm and about 51-52 wt.% of it was smaller than 5.6 mm in a landfill containing 1-10 years old waste (MSW), whilst a site with 24-40 years old waste (MSW + C&D + soil) presented ratios of 88-93 wt.% and 66-74 wt.% (except one sample having 40 wt.% under 5.6 mm), respectively, for the same fraction.

Miller, Earle, & Townsend, 1996 reported that most (around 99%) of the landfill cover soil passed through a sieve of 0.425 mm, while retaining a majority of the biodegradable material. The fine fraction < 0.425 mm was composed mainly of sand, which had the lowest organic matter content of all three fractions. Moreover, together the fractions < 0.425 mm and 0.425-6.3 mm constituted about 60

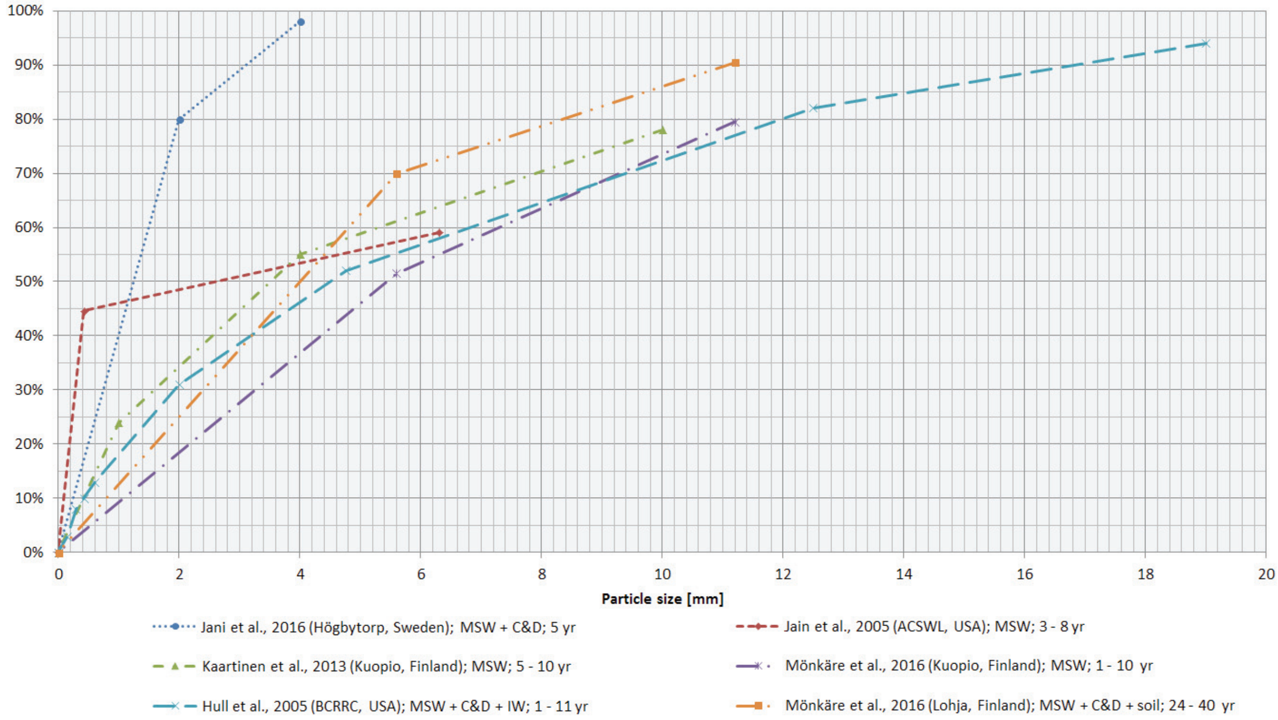

FIGURE 1: Particle size distribution within excavated fine fractions from previous LFM investigations.

wt.% of the excavated landfill MSW (3-8 years old) by Jain et al., 2005; where 44.6 wt.% corresponded to the fraction < 0.425 mm and 14.5 wt.% to the fraction 0.425-6.3 mm.

Excavated landfill MSW (10 years old waste), which consisted of around 54 wt.% material < 40 mm and about 46 wt.% material > 40 mm, exhibited a slight increase in the amount of the material < 40 mm with depth (Burlakovs, Kaczala et al., 2016; Bhatnagar et al., 2017). The results obtained by Kaartinen et al., 2013 indicated transport of the fraction < 20 mm (5-10 years old excavated MSW) towards the bottom layer of the landfill as well. The age of the disposed waste can affect the particle size distribution in a landfill (Hull et al., 2005); several fractions of the older waste (7-11 years old MSW + C&D + IW) presented greater amounts of material < 25.4 mm. Thus, it can be inferred that the amount of fine fractions might increase over time due to the reduction of the particle size of certain waste materials, mainly organic materials, driven by biodegradation and weathering effects. However, it is relevant to point out that a larger amount of fine particles can be found in deeper layers of the landfill due to vertical transport (i.e. downward migration due to gravitational force) rather than biodegradation and weathering effects, which could mislead to the consideration of higher values for the decrease in particle size due to degradation of waste over time.

Other interesting findings include that, for example, a visual inspection by Kaartinen et al., 2013 indicated that the fraction < 4 mm was predominantly composed of soil. Spooren et al., 2012 reported an average of 43 wt.% for the fraction < 10 mm from excavated landfill MSW (14-29 years old material). Hull et al., 2005 suggested that in order to remove all visual contaminants a 2 mm screen is to be employed, since non-soil materials such as plastic, paper flakes and broken glass generally did not pass through; in this manner the mass of the fraction < 25.4 mm could be reduced by about 70% as well.

According to Spooren et al., 2012, common industrial waste separation techniques are unable to sort materials with a particle size below a certain threshold, which often lies within the range of 2-10 mm.

From the gathered information above it can be extracted that: the amount of the fine fractions in landfilled MSW seems to increase over time, whereas their particle size seems to decrease; in a landfill a larger amount of fines could be expected with depth; most of the material composing the fine fractions from excavated landfill MSW is likely to have a particle size larger than 1 mm; most of non-soil materials such as plastics, paper, textiles, stones and broken glass and ceramics could be removed through sieving (probably around 2 mm); the under-sieve material could be expected to be mainly soil-like material (including inert materials) and landfill cover soil and fine inert materials could be recovered via further finer sieving (probably around 0.5 mm).

Therefore, it is relevant to emphasize that in LFM and ELFM future investigations the particle size will be a key parameter for the separation of the fine fractions into exploitable resources and the minimization of the material to, if the case, be sent back for re-landfilling. For this, the fine fractions may be classified into certain particle size ranges, selected according to the results of the material characterization and particle size distribution during the exploration phase of a LFM project, to determine the cut-off diameter size for the fine fractions and enable more efficient material recovery, for different purposes (e.g. recycling and alternative fuel), and recuperation of soil-like and inert materials in the corresponding processing techniques (e.g. density, magnetic and eddy-current separators, among others). This can result very useful to implement a material processing approach especially designed for the particular characteristics of each particle size range, as well as to concentrate some of the moisture and undesired substances (e.g. heavy metals) into a few of the finest particle size ranges.

3.3 Moisture and organic content

The moisture content of the excavated waste is an important characteristic that determines the environmental conditions in the landfill and plays an important role when considering the material processing (Hull et al., 2005). In a landfill it depends on many interrelated factors, such as waste composition (e.g. percentage of organic matter, plastics, inert, etc.), waste type (e.g. MSW, C&D, Industrial waste), waste properties, local climate and weather conditions, landfill operation procedures, gas and leachate collection systems, water generation and consumption due to microbiological activity, between others (Qian, Koerner, & Gray, 2002). Moisture is predominantly present in the fine fractions, as small pores hold water stronger than large pores (capillary action). This is why moisture is a key parameter regarding the treatment of the fine fractions.

Moreover, moisture is one of the most relevant factors influencing the biodegradation of organic matter, playing a vital role in all microorganism´s metabolism, and, hence, it is highly interrelated with the organic content in a landfill (Bäumler & Kögel-Knabner, 2008). The water content is also related to the organic content because organic matter can store a manifold of its own weight of water; this is also valid for certain types of clay minerals. Furthermore, the microbial activity and organic matter play a very important role in the absorption and mobilization of metals (Bozkurt, Moreno, & Neretnieks, 1999; Bradl, 2005).

The water content of the excavated waste can vary significantly and needs to be taken into account when assessing the valorization and treatment options for ELFM (Quaghebeur et al., 2013). It is to be noted that the sampling procedure and the approach with which the water content is determined might have relevant effects on the determined value and, hence, the real water content might differ from the calculated value. For example, the calculated water content can result in a lower value due to water losses during sampling and sieving activities.

Previous experiences include that moisture contained in excavated waste did not impede its processability, but it might have affected the processing efficiency (Kaartinen et al., 2013). Thus, some studies have recurred to the drying of the fines fraction for better results (Hull et al., 2005; Jain et al., 2005; Kaartinen et al., 2013; Kurian et al., 2003; Prechthai et al., 2008; Quaghebeur et al., 2013). Drying of the fine fractions could: (i) reduce the amount of surface defilements; increasing the quality of the recyclable materials and raising the efficiency of sorting processes, especially for the sensor-based sorting technologies, such as near infrared (NIR) and color recognition (VIS), (ii) enable a more efficient and precise particle size classification in the screening and sieving processes, (iii) decrease the total amount of material to be processed and, perhaps, transported and (iv) raise the calorific value.

An additional study by Jain et al., 2005, investigated differences regarding physical appearance, such as presenting darker color, smaller particle size and higher degree of degradation for landfill-mined material which has been previously exposed to leachate recirculation; while no significant difference was observed in the mean moisture content when compared with landfill-mined material without leachate recirculation.

Like the moisture also the organic matter is enriched in the fine fraction, as degradation processes of biowaste decrease its grain size over time in a landfill. Table 4 shows the results obtained on moisture and organic contents from various LFM studies. Into this respect it can be observed that the moisture content varies between 16 and 54 wt.% and the organic matter content between 9 and 21 wt.% (dry matter) for landfills with comparable ages (up to 10 years) and type (MSW) of disposed material, as well as similar particle sizes (< 20 mm); while for older excavated material (17 to 40 years old) the moisture and organic content seem to decrease slightly to ranges of 18-40 wt.% and 5-14 wt.% (dry matter), respectively.

The decrease of organic matter content with the increase of the age of the waste was also observed by Mönkäre et al., 2016 and Hull et al., 2005. This showed congruency with the results obtained by Francois et al., 2006 as well, indicating that younger material is less degraded than older material. Thirty year old material presented volatile solid contents (VS) characteristics for stabilized material (Kelly, 2002). Ayuso, Hernández, García, & Pascual, 1996 reported that the organic matter content of 30 year old material were close to the characteristics of soil. In this respect, a model (Tabasaran & Rettenberger, 1987) can be used to estimate the organic decay in landfill through the prognosis of landfill gas generation.

It has been observed that organic matter influences the capacity of waste to hold water, known as field capacity (Sormunen et al., 2013; Zornberg, Jernigan, Sanglerat, & Cooley, 1999). The higher the content of organic matter, the higher is the water content to be expected (Hull et al., 2005). The biodegradable organic matter content in the waste reported by Zhao et al., 2007 was significantly higher than in the cover soil used at the landfill.

The contents of total and volatile solids determined by Mönkäre et al., 2016 showed no trends regarding site or depth and her results indicate that organic matter can remain for a long time in a landfill, which is explained by the formation of stable humic substances during the biodegradation of organic matter. Volatile solids, despite not a measure of available organic matter, might be a simple and inexpensive way to assess the potential degradability of the excavated waste from a landfill (Hull et al., 2005).

The composition of the cover layer employed at a site seems to play a relevant role regarding the waste degradation rate; meaning that the degradation process could be significantly faster with the use of a high to medium permeability material (e.g. compost) than with a low permeability one (e.g. clay) (Francois et al., 2006). This can be explained by the fact that the use of a permeable material as cover

TABLE 4: Organic content, total solids and water content of excavated fine fractions from previous LFM investigations.

Parameter	(Filborna, Sweden) in Kurian et al., 2003	Bhatnagar et al., 2017 (Kudjape, Estonia)	Hull et al., 2005 (BCRRC, USA)	Kurian et al., 2003 (Perungudi, India)	Mönkäre et al., 2016 (Kuopio, Finland)	Kurian et al., 2003 (Kodungaiyur, India)	Mönkäre et al., 2016 (Lohja, Finland)	Gutiérrez-Gutiérrez et al., 2015 (4 sites in UK)	Hogland et al., 2004 (Maasalycke, Sweden)	Jani et al., 2016 (Högbytorp, Sweden)	(Deonar, India) in Kurian et al., 2003
Type of waste disposed of	MSW	MSW	MSW + C&D + IW	MSW	MSW	MSW	MSW + C&D + soil	MSW and MSW + C&I	MSW	MSW + C&D	MSW
Age of waste [a]	-	10	1 - 11	0 - 10	1 - 10	10	24 - 40	-	17 - 22	5	-
Particle size [mm]	< 40	< 40	< 25.4	< 20	< 20	< 20	< 20	< 19	< 18	< 10	< 8
Organic content	-	-	-	8.9 - 15.8%	8.8 ± 0.4 - 16.9 ± 0.7%	8.9 - 20.7%	4.9 ± 0.4 - 14.3 ± 0.8%	25.0 ± 10.0 - 41.0 ± 9.0%	-	16.6%	14.5%
Total solids	-	-	-	-	46.2 ± 1.7 - 63.7 ± 1.7%	-	59.6 ± 1.6 - 81.6 ± 1.0%	-	-	-	-
Water content	30.0 - 38.0%	≤ 40.0%	16.0 - 43.0%	21.4 - 52.0%	-	15.5 - 46.0%	-	58.0 ± 70. - 79.0 ± 9.0%	22.3 - 28.8%	23.5%	14.0%
Notes:	*Information organized according to particle size* *Figures have weight basis* *MSW - Municipal solid waste* *C&D - Construction and demolition waste* *IW - Industrial waste* *PPC - Paper, paperboard and cardboard*										

layer in a landfill could favor the aerobic biological degradation of certain organic components, which degrade at a faster rate in aerobic than in anaerobic conditions. This could mean that waste from landfill sites where low permeability cover materials were used might present higher organic content, which could eventually be found in the fine fractions. Nonetheless, the use of compost as cover material might raise the organic content of the fine fractions as well.

Studies in Europe on fresh organic MSW have revealed that the average total organic carbon remains relatively stable, around 43-44 wt.%, despite the heterogeneity of the organic matter content (Baky & Eriksson, 2003; Iglesias Jimenez & Perez Garcia, 1992), suggesting that the variation of this parameter in the fine fractions from LFM depends strongly on the treatment of the MSW before disposal and the conditions at the landfill site.

From this information it can be concluded that significant amounts of organic matter and moisture are likely to be present in LFM material and, eventually, to be found in the fine fractions. These interrelated parameters are of critical relevance, since processing routes and possible end-uses for these fractions will depend on their quantities. Depending on the amount of moisture it can be determined if a dry or wet further processing of the material is to be employed and the efficiency of the chosen method will depend considerably on the moisture content. The organic content can be used to determine if material or energy recovery routes should be pursued or, otherwise, if the material is suitable to be re-landfilled according to the legislation in force.

Fine fractions might be used in the future to predict the moisture content in samples containing all fractions, as results on moisture between samples of fines and samples containing all fractions have shown good correlation and representative samples of the fines are easier to take than those containing all fractions (Hull et al., 2005).

3.4 Physico-chemical properties

Table 5 displays data on some physico-chemical properties of the fine fractions obtained in the reviewed investigations. This information shows that most of the compared parameters presented roughly similar ranges within different sites, taking into account the differences among them (mainly in particle size and age of waste).

Characteristics such as calorific value, amount of organic carbon, total carbon, ash content, hydrogen and nitrogen contents are needed to assess the efficiency for WtE applications (Quaghebeur et al., 2013).

Most physical, chemical and microbial processes, such as dissolution of waste materials and metabolites and emissions of volatile substances, as well as the pressure conditions, in a landfill are affected by temperature (Hull et al., 2005). The temperature of landfilled waste has been seen to increase with a rate of approximately 1 °C per m of depth (Attal, Akunna, Camacho, Salmon, & Paris, 1992; Gurijala & Suflita, 1993; Hull et al., 2005; Zornberg et al., 1999). Temperature also plays a decisive role regarding microbiological activity and biochemical reactions inside the landfill, which are linked in parallel to the moisture, organic matter content and pH, among others.

The calorific value of a waste fraction is mainly driven by the amount of carbon (usually measured as total carbon or total organic carbon) and the ash and moisture contents.

Chemically, fine fractions of landfill mining consist mainly of SiO_2, CaO, Al_2O_3 and FeO (Spooren et al., 2012). However, the recovery of these compounds is limited by the presence of environmentally problematic elements, especially heavy metals. Nevertheless, the environmental impact of a material does not depend on its total content of hazardous substances, but on their mobility. Some parameters of significance in control of metal mobility such as pH, sulfide, sulfate and chloride contents in a landfill have been studied by Gould, Cross, & Pohland, 1990; the latter reported that a broad range of attenuating mechanisms limiting the mobility of toxic metals in the leachate from columns simulating landfill material with shredded MSW occurred, suggesting that MSW has a capacity for minimizing the mobility of heavy metals.

The values for pH and phosphorous of the fines fraction complied with the limits for compost standards, while the contents of N and K did not (Prechthai et al., 2008). The variation of pH towards the bottom of a dumpsite show the varying decomposition rate of organic waste (Das, Smith, Gattie, & Hale Boothe, 2002; Townsend, Miller, Lee, & Earle, 1996). It is known that the pH of waste varies over time in a landfill depending on the phase the waste is going through, i.e. aerobic phase, anaerobic phase (acidic and methanogenic phases) and humic phase; where the waste presents a pH close to 7 units at the beginning, decreases to about 4-6 units in the acidic phase, raises back to around 7-8 units during the methanogenic phase and remains slightly basic, approximately 8 units, for the humic phase (Bozkurt et al., 1999). The humic phase is reached when all the readily degradable organic matter has been degraded and remains in the waste in a very stable substance state (Bozkurt et al., 1999). This suggests that the pH of the waste in a landfill can be expected to decrease with depth in some cases; depending on the characteristics of the site, operational procedures and type of waste contained. Nonetheless, it is to be considered that due to the strong heterogeneity in a landfill, different parts of the landfill might develop at different rates (Bozkurt et al., 1999) and, thus, a decreasing tendency of the pH with depth might not be always the case. A pH variation within the range of 4-9 units was observed in the reviewed investigations displayed in Table 5. Low pH and high TOC values are indicators of incomplete biodegradation of the material (Kurian et al., 2003).

The nutrient contents were low for two observed landfills; especially total phosphorus was below detection limit of 10 mg/kg (dry matter) in most sampling points (Mönkäre et al., 2016). Results obtained by Hogland et al., 2004 for total phosphorus showed similar concentrations. Values for fresh biowaste from household waste in Denmark

TABLE 5: Physico-chemical properties of excavated fine fractions from previous LFM investigations.

Parameter	(Filborna, Sweden) in Kurian et al., 2003	Wolfsberger et al., 2015 (Lower Austria, Austria)	Hull et al., 2005 (BCRRC, USA)	Prechthai et al., 2008 (Nonthaburi, Thailand)	Kurian et al., 2003 (Perungudi, India)	Mönkäre et al., 2016 (Kuopio, Finland)	Kaartinen et al., 2013 (Kuopio, Finland)	Kurian et al., 2003 (Kodungaiyur, India)	Mönkäre et al., 2016 (Lohja, Finland)	Hogland et al., 2004 (Maasalycke, Sweden)	Jani et al., 2016 (Högbytorp, Sweden)	Kaczala et al., 2017 (Kudjape, Estonia)	Quaghebeur et al., 2013 (REMO, Belgium)	(Deonar, India) in Kurian et al., 2003
Type of waste disposed of	MSW	MSW	MSW + C&D + IW	MSW	MSW	MSW	MSW	MSW	MSW + C&D + soil	MSW	MSW + C&D	MSW	MSW	MSW
Age of waste [a]	-	13 - 20	1 - 11	3 - 5	0 - 10	1 - 10	5 - 10	10	24 - 40	17 - 22	5	5 - 6	14 - 29	-
Particle size [mm]	< 40	< 40	< 25.4	< 25	< 20	< 20	< 20	< 20	< 20	< 18	< 10	< 10	< 10	< 8
Ash content	78.9%	-	-	68.6%	84.2 - 91.1%	-	-	79.3 - 91.1%	-	87.3 - 90.2%	-	-	64.4-85.0%	-
Bulk density [kg/m³]	400 - 500	-	370 - 1,206	-	745 - 1,147	-	-	853 - 1,254	-	-	690	-	-	-
Calorific value [MJ/kg]	-	4.4 - 9.0	-	-	-	-	-	-	-	0.4 - 0.9	1.7	-	2.2 - 4.8	-
pH	4.0 - 5.0	-	-	7.7 ± 0.3	7.6 - 8.6	6.8 - 7.6	8.1 ± 0.1 - 8.3 ± 0.1	6.9 - 8.1	7.2 - 7.9	7.0 - 7.3	7.7	7.1 - 8.3	-	7.2
Total organic carbon	13.0%	10.0 - 20.0%	-	-	5.2 - 7.9%	4.7 - 5.6%	4.7 ± 0.8 - 5.8 ± 1.6%	4.5 - 10.4%	-	-	5.6%	0.2 - 0.4%	7.6 - 12.4%	5.8%
Notes:	*Information organized according to particle size* *Percentage figures have weight basis* *MSW - Municipal solid waste* *C&D - Construction and demolition waste* *IW - Industrial waste*													

for nitrogen content reported by Riber, Petersen, & Christensen, 2009 were significantly higher than the ones from landfilled material reported by Hogland et al., 2004 and Mönkäre et al., 2016. This reflects the consumption and migration of the nutrient content in the fine fractions after disposal. Total nitrogen and phosphorus measurements by Zhao et al., 2007 in fine fractions indicated that nitrogen levels decrease over time, whereas phosphorus levels remain steady; the measured contents of these elements in the fine fractions were higher than in the cover layer.

The chemical oxygen demand and heavy metals, chlorides and fluorides contents in leachate of the fine fractions can be useful to identify the ability to reuse these fractions as a construction material outside the landfill, landfill cover material or for landfilling as inert material (Jani et al., 2016). The sulfur, chlorine, fluorine and bromine content of waste is needed to assess the emission levels during thermal conversion (Quaghebeur et al., 2013).

According to Kaartinen et al., 2013, the fine fractions exhibited generally non-hazardous properties in leaching tests performed to assess landfill acceptability; nevertheless, leaching of dissolved organic carbon from fine fractions of young disposed MSW may be challenging for landfill disposal in the EU. Therefore, pH-dependent leaching tests (e.g. European standard EN 14429) might result essential to identify the recycling possibilities of waste materials like the fine fractions.

Jani et al., 2016 reported that the calorific value, methane gas potential and total organic carbon decreased with the time waste has been disposed of, since lower values were obtained for the waste in older layers of the landfill, where the organic materials showed a larger decomposition. The determination of the methane potential could be used to identify the suitability of the fine fractions for energy recovery or the need for stabilization to prevent emissions (Mönkäre et al., 2016).

As shown in Table 5, mostly low heating values (between 0.4-4.8 MJ/kg) were reported for the fine fractions in previous LFM studies (Hogland et al., 2004; Jani et al., 2016; Quaghebeur et al., 2013). Nonetheless, Wolfsberger et al., 2015 obtained higher values (around 4.4-9 MJ/kg). As already stated, moisture, carbon and ash contents are highly interrelated with respect to the calorific value and, despite the lack of information regarding these parameters for some of the compared studies, it could be observed that the highest calorific value range (4.4-9 MJ/kg) corresponds to the highest total organic content range (10-20 wt.%), whereas the lowest calorific value range (0.4-0.9 MJ/kg) corresponds to the highest ash content range (87.3-90.2 wt.%).

There was not enough comparable information in the studies presented in Table 5 to identify a correlation between particle size and age of waste regarding the calorific value. Nevertheless, additional previous investigations reported that the calorific value and total organic carbon concentration decreased with increasing storage time of the waste in the landfill; what is most likely the result of decomposition of carbon-rich material into landfill gas over time (Quaghebeur et al., 2013). The analyses from Masi et al., 2014 show that the fraction < 4 mm has a percentage of the total organic carbon more than six times higher than a conventional agrarian soil.

The bulk density showed a variation from 370 to 1,254 kg/m^3 in Table 5; where the lowest density range (400-500 kg/m^3) corresponds to the coarsest particle size (< 40 mm) from the compared studies. The highest bulk density ranges (853-1,254 and 745-1,147 kg/m^3) corresponded to a particle size of < 20 mm, which was not the finest particle size from the compared studies but presented the highest ash content ranges (79.3-91.1 and 84.2-91.1 wt.%).

The cellulose content, cellulose-to-lignin or cellulose-to-VS ratios have been used in MSW decomposition studies as an indicator of degradation grade of the waste in landfills (Bookter & Ham, 1982; Ham, Norman, & Fritschel, 1993; Jones, Rees, & Grainger, 1983; Mehta et al., 2002; Wang, Byrd, & Barlaz, 1994). A cellulose-to-lignin ratio of < 0.2 (30 year old waste) indicates relatively well stabilized waste compared to less degraded waste with a ratio of 0.9-1.2 and fresh waste with a ratio of 4 (Bookter & Ham, 1982). These ratios could be used to determine the degree of degradation of the fine fractions and, thereby, evaluate their material or energy recovery potential.

Phytotoxicity was tested by Masi et al., 2014, which reported that the acute tests did not demonstrate particularly adverse effects on the growth of test species for two of three species. According to the results obtained by Prechthai et al., 2008 the phytotoxicity of waste to inhibit the germination of rice seed was relatively low and signified the completed degradation of organic matter in the fines fraction; suggesting the safe and suitable usage of the material as compost for non-edible crops. For this, materials like stone, glass, metal and plastics, which can be a problem in the soil, are to be removed (Masi et al., 2014; Prechthai et al., 2008). However, it has to be considered, that limit values with respect to the total and leachable contents of environmentally problematic substances can be far below the concentrations which yield a visible effect in ecotoxicity tests. Consequently, the lacking phytotoxicity of a material does not allow its recycling per se.

3.5 Metals content

Table 2 shows that the contents of total metals in LFM fine fractions were relatively low regarding metal recovery potential; except for a site in the USA, where the disposal of industrial waste (IW) and construction & demolition waste (C&D) together with MSW was registered, and a site in Sweden, where the upper limit of the fine fraction was set at a coarser particle size (< 40 mm). The latter presented a considerably higher amount of metals than a study in Austria that contained the same type of waste (only MSW) and used the same particle size as upper limit for the fines fraction (Wolfsberger et al., 2015). Spooren et al., 2012 found an amount of 3±2 wt.% of ferromagnetic material (such as ferromagnetic metals and metal oxides) in the fraction < 10 mm of excavated landfill MSW with respect to the same fraction.

Furthermore, amounts of around 99.9% metals and around 90% non-metals, of their whole amount within the fines, have been reported as still found in the fines at the beginning of the humic phase by Belevi & Baccini, 1989 and

Bozkurt et al., 1999, showing low degradation of metals in a landfill.

It is relevant to mention that the removal of metals could be negatively influenced when the reach of the metal sorting equipment is limited to larger particle sizes or the metals present poor quality, as they might be oxidized and in degraded conditions.

Nonetheless, there have been additional studies where the amount of metals has been found in significant concentrations, such as a study on the content of metallic elements in the fraction < 10 mm, at different depths, of the excavated waste from a MSW landfill (Burlakovs, Kaczala et al., 2016), which unveils that interesting concentrations of several metals with respect to material recovery, i.e. Fe (average concentrations above 10,000 mg/kg), Mg and Zn (average concentrations above 1,000 mg/kg), can be found in the fine fractions of landfilled waste, as well as concentrations above 100 mg/kg of metals like Mn, Ba, Cu, Pb and Sr. Also, results on the fraction < 40 mm show that the metal content (mainly Fe, Al and Cu) was about 0.6 wt.% of the same fraction (Burlakovs, Kriipsalu et al., 2016). Significant concentration ranges of Al (12,079-17,274 mg/kg) and Cu (1,027-2,595 mg/kg), in waste mined from landfills were reported by Gutiérrez-Gutiérrez, Coulon, Jiang, & Wagland, 2015. Bhatnagar et al., 2017 identified 1 wt.%, of the total amount of the fraction < 40 mm, of Fe, Cu and Al in the same fraction.

Additionally, the amount of magnetic metals recovered from a full-scale process by Kaartinen et al., 2013 was around 1 wt.% from the total processed waste; moreover, this amount was smaller than the amount of total metals separated by manual sorting, which was 3-4 wt.%. Al and Fe recovery from the fine fractions are of interest; as their concentrations in the fines could yield around 2-2.5 wt.% of Al and 1.5-2 wt.% of Fe of the total amount of the same fraction (Kaartinen et al., 2013).

Chemical analyses of fine fractions do not give information about the oxidation state of metals. However, under landfill conditions it is obvious that metals like Ca, Mg, K and Na, but also a significant proportion of Fe are present in oxidized form as minerals. Among these, Ca and Fe were the metals with higher concentration ranges, with 70,000-80,000 mg/kg and 30,000-50,000 mg/kg, respectively, in the fraction < 10 mm; followed by Mg, K, Na and Zn (concentrations between 500-20,000 mg/kg), Mn, Cu and Pb (concentrations around 150-400 mg/kg) and Cr, Ni, Co and Cd (concentrations below 150 mg/kg), according to Bhatnagar et al., 2017. A similar trend in terms of metal concentrations was found between all excavated pits (Bhatnagar et al., 2017). Interesting concentrations of zinc, copper, barium and chromium for metals recuperation were found by Jani et al., 2016 in the fine fractions.

It is relevant to note that the mineralogical bonding of the individual metals has to be considered when assessing the metals recovery potential of a particular site; as the total amount (mixed with minerals and other materials), the metallic amount and the amount found in compounds (e.g. oxides) of these elements play a crucial role in the determination of the recoverable amount and their speciation.

Moreover, fractions (< 10 mm) of excavated industrial waste can contain higher magnetic metals concentrations than mined MSW, seeing that a concentration of around 0.5-5.3 wt.% of ferromagnetic material was obtained from MSW and one of about 25-29 wt.% from IW by Spooren et al., 2012 and Quaghebeur et al., 2013. This can be corroborated with the results obtained by Hull et al., 2005 presented in Table 2; in which the metals content was higher in a site where MSW, C&D and IW were landfilled than in the sites where solely MSW was registered. The analysis of previous studies focused on mining industrial waste from landfill is not within the scope of the present review; nonetheless, the recuperation of metals from landfills for industrial waste might result interesting for future review.

According to the preliminary results obtained by Quaghebeur et al., 2013 the removal of the magnetic metals from the fraction < 10 mm could result in a reduction of more than 50 wt.% of the total amount of metals in the same fraction.

The previous information suggests that mechanical processing technologies still have optimization potential for higher yields.

Table 6 encompasses data gathered on specific metals, mainly heavy metals, found in the fine fractions in LFM studies carried out in the past. Heavy metals might accumulate in the fine fractions due to their high specific surface area for interaction (Jain et al., 2005; Wolfsberger et al., 2015). This suggests that a significant part of these heavy metals occur as dissolved species in the pore water or as oxidized precipitates at particle surface. Consequently, the recovery of these metals must include reduction to their elementary state, which would be associated with significant effort.

The results obtained by Masi et al., 2014 showed that the composition of very old dumpsites is relatively uniform and that the concentrations of heavy metals in the fraction < 4 mm were, on average, 30% lower than in the fraction 4-10 mm. This suggests that besides the part which is dissolved, adsorbed or that occurs as fine-grained precipitates, another portion of heavy metals might occur in its metallic state. Furthermore, the classification of the fine fractions into determined particle size ranges might be a way to identify and select more accurately the necessary mechanical processing for each particle size range; enabling a more efficient and appropriate processing according to the properties and material recovery potential of each particle size range.

The heavy metal concentration in the waste fractions to be revalorized as refuse derived fuel (RDF) is also to be taken into consideration (Rotter, Kost, Winkler, & Bilitewski, 2004). It is possible that high concentrations of hazardous substances and heavy metals are found in local pockets (Kurian et al., 2003), since elements such as As, Cd, Co, Cr, Cu, Ni, Pb, Hg and Zn can be found in household products (Slack, Gronow, & Voulvoulis, 2005) and, therefore, in landfill leachate (Reinhart, 1993) depending on the solubility of the respective phases.

For instance, the highest concentrations of Cr and Pb found by Prechthai et al., 2008 were in the fine fractions; which was in accordance with the findings reported by Hogland et al., 2004. High concentrations of Cd and Pb

TABLE 6: Metals content in excavated fine fractions from previous LFM investigations.

Parameter	Wolfsberger et al., 2015 (Lower Austria, Austria)	Hull et al., 2005 (BCRRC, USA)	Prechthai et al., 2008 (Nonthaburi, Thailand)	Kurian et al., 2003 (Perungudi, India)	Kaartinen et al., 2013 (Kuopio, Finland)	Kurian et al., 2003 (Kodungaiyur, India)	Hogland et al., 2004 (Maasalycke, Sweden)	Zhao et al., 2007 (Shanghai, China)	Jani et al., 2016 (Högbytorp, Sweden)	Kaczala et al., 2017 (Kudjape, Estonia)	Bhatnagar et al., 2017 (Kudjape, Estonia)	Quaghebeur et al., 2013 (REMO, Belgium)	Masi et al., 2014 (Lavello, Italy)	Jain et al., 2005 (ACSWL, USA)	Masi et al., 2014 (Lavello, Italy)	Jain et al., 2005 (ACSWL, USA)
Type of waste disposed of	MSW	MSW + C&D + IW	MSW	MSW	MSW	MSW	MSW	MSW	MSW + C&D	MSW	MSW	MSW	MSW	MSW	MSW	MSW
Age of waste [a]	13 - 20	1 - 11	3 - 5	0 - 10	5 - 10	10	17 - 22	8 - 10	5	5 - 6	10	14 - 29	30 - 60	3 - 8	30 - 60	3 - 8
Particle size [mm]	< 40	< 25.4	< 25	< 20	< 20	< 20	< 18	< 15	< 10	< 10	< 10	< 10	< 10	0.425 - 6.3	< 4	< 0.425
Ag [mg/kg]	-	-	-	-	-	-	-	-	-	-	-	-	-	< 1.5 - 24.6	-	< 1.5 - 23.8
Al [g/kg]	-	-	-	-	51.0 ± 10.0 - 57.0 ± 3.1	-	-	-	-	-	-	-	-	2.5 - 169.0	-	1.9 - 76.1
As [mg/kg]	16.0 - 23.0	9.1 ± 8.6	-	0.1 - 1.6	-	0.8 - 5.6	< 0.4	-	5.1 ± 1.7	-	-	27.1 ± 15.0	73.0	1.1 - 58.6	68.0	0.2 - 10.1
Ba [mg/kg]	-	-	-	-	1,100 ± 100 - 900 ± 300	-	-	-	468.0 ± 143.0	-	-	-	-	13.8 - 681.0	-	8.2 - 70.0
Ca [mg/kg]	-	-	-	-	85,000 ± 39,000 - 65,000 ± 12,000	-	-	-	-	-	20,000 - 60,000	-	-	-	-	-
Cd [mg/kg]	1.6 - 4.8	1.2 ± 1.2	4.2	0.8 - 1.8	≤ 100	0.9 - 3.1	0.9 - 1.2	1.1 - 10.7	2.1 ± 0.6	-	0 - 5	5.9 ± 3.8	54.0	< 0.3 - 40.0	55.0	< 0.3 - 13.8
Co [mg/kg]	6.6 - 17.0	-	-	-	-	-	-	-	23.3 ± 5.8	-	5 - 10	-	-	< 0.5 - 86.7	-	< 0.5 - 32.9
Cr [mg/kg]	130.0 - 170.0	26.0 ± 24.0	166.6	110.0 - 261.0	100 ± 100 - 200 ± 100	191.0 - 657.0	47.0 - 78.0	73.5 - 252.1	254.0 ± 54.0	-	10 - 100	495.7 ± 118.0	145.0	9.5 - 531.0	117.0	2.5 - 151.0
Cu [mg/kg]	-	-	2,245.0	75.0 - 217.0	800 ± 1,200 - 200 ± 100	127.0 - 968.0	34.0 - 36.0	-	1,460.0 ± 684.0	45.3 - 105.2	100 - 300	339.3 ± 55.3	1,067.0	5.8 - 5,530	538.0	0.7 - 170.0
Fe [mg/kg]	-	-	-	-	37,000 ± 1,700 - 41,000 ± 2,100	-	-	-	28,724 ± 8,108	-	20,000 - 60,000	27,000 ± 750	-	4,600 - 61,800	-	800 - 28,200
Hg [mg/kg]	0.4 - 0.6	0.4 ± 0.4	-	0.04 - 0.8	-	0.6 - 2.7	0.2 - 0.3	-	0.7 ± 0.2	-	-	0.7 ± 0.5	-	0.04 - 9.0	-	< 0.04 - 1.8
K [mg/kg]	-	-	0.2 ± 0.1	-	16,000 ± 2,900 - 17,000 ± 2,100	-	-	-	-	-	500 - 20,000	-	-	-	-	-
Mg [mg/kg]	-	-	-	-	12,000 - 12,000 ± 600	-	-	-	-	-	500 - 20,000	-	-	-	-	-
Mn [mg/kg]	-	-	947.0	-	700 ± 100 - 1,300 ± 400	-	-	-	-	-	100 - 500	-	3,385.0	50.4 - 14,700	1,241.0	6.2 - 993.0
Mo [mg/kg]	-	-	-	-	< 100 - 100 ± 100	-	-	-	18.8 ± 3.9	-	-	-	-	-	-	-
Na [mg/kg]	-	-	-	-	19,000 ± 2,100 - 21,000 ± 2,500	-	-	-	-	-	500 - 20,000	-	-	-	-	-
Ni [mg/kg]	45.0 - 60.0	-	47.8	21.0 - 50.0	100.0	31.0 - 247.0	14.0 - 15.0	-	111.4 ± 33.7	-	10 - 100	176.3 ± 60.7	138.0	6.4 - 743.0	89.0	0.8 - 340.0
Notes:	*Information organized according to particle size / MSW - Municipal solid waste C&D - Construction and demolition waste / IW - Industrial waste*															

were found in the fine fractions by Wolfsberger et al., 2015. Arsenic was determined to come mainly from the waste rather than from the soil cover (Jain et al., 2005).

In general, heavy metals commonly demonstrate high levels of sorption and precipitation; mercury has been predominantly found as resistant to leaching in landfills (Slack et al., 2005). Only trace levels of volatile heavy metals (As and Hg) have been detected in landfill gas whereas particulate matter contributes more to the emissions of heavy metals from landfills (Parker, Dottridge, & Kelly, 2002). Most of the contaminants released from fine fractions can be found in particulate matter (Kaczala et al., 2017); this suggests that they could be removed using physical methods. Mn, Cd and Zn showed low mobility potential under aerobic conditions in the study of Prechthai et al., 2008 as well. Poor solubility of heavy metal containing phases and slow leaching kinetics of heavy metals in water was reported by Kurian et al., 2003, since the heavy metal concentrations in water extract were lower than of leachate.

Results (Gutiérrez-Gutiérrez et al., 2015) indicate that the leachate is not mobilizing vertically critical metals (critical raw materials – CRMs, according to EU´s criteria) in the landfill, since no direct relationship between depth and concentration has been reported consistently for these metals. Leaching tests done by Kaczala et al., 2017 on landfill-mined material (particle size < 10 mm) for heavy metals such as Zn (0.5-0.9%), Cu (0.2-0.6%) and Pb (0.9-1.1%) have shown low average leaching ratios (leached amount/amount in solid waste matrix). Low leaching ratios for Cu (0.2%), Zn (6.1%) and Pb (0.7%) from under-sieve (< 20 mm) residues, prior to landfilling, were obtained by Cossu & Lai, 2012 as well. However, limit concentrates in the leachate are often very low (< 1 mg/kg dry matter) so that even the leaching of few per mil of the total heavy metal content leads to an excess of limit values.

Other studies on landfills have also reported very low leaching of heavy metals out of the landfill compared to the accumulated amount (Baccini, Henseler, Figi, & Belevi, 1987; Belevi & Baccini, 1989; Finnveden, 1996; He, Xiao, Shao, Yu, & Lee, 2006; Øygard, Måge, & Gjengedal, 2004); where most of the heavy metals were found retained within the waste matrix. Contaminants such as heavy metals will remain in the waste unless leached out (Jain et al., 2005).

Moreover, studies have reported low leaching rates of heavy metals over relatively long periods of time (Esakku, Palanivelu, & Joseph, 2003; Gould et al., 1990; Kjeldsen et al., 2002; Reinhart & Basel Al-Yousfi, 1996; Ross, Harries, Revans, Cross, & NATHANIEL, 2000).

These previous results and experiences suggest that these elements are most likely to be found in the fine fractions even in older landfills and that their relevance for the feasibility of landfill mining should not be overseen.

Nonetheless, the leaching rate of heavy metals in landfill waste can be influenced by several factors. For example, in an open dumpsite, where the oxygen diffusion rate can be high, the conditions for the leaching of heavy metals out of the waste matrix could be favored (Martensson, Aulin, Wahlberg, & Agren, 1999). The content of organic compounds in landfilled waste considerably influences the mobility of metals; it either tends to increase the sorption of metals and delay their release or promote their mobilization (Gutiérrez-Gutiérrez et al., 2015). So the particular conditions of each site must be carefully assessed as one of the first steps.

Younger landfills show lower concentrations of As, Cd, Cr, Cu, Hg, Ni, Pb and Zn in the fine fractions than old ones; this can most likely be attributed to an improved initial quality of the fresh MSW over time (Quaghebeur et al., 2013), e.g. due to separate collection of waste electric and electronic equipment (WEE).

Elements like copper, iron, zinc and rare earth metals are being depleted in their primary sources and there is an increasing demand on these elements due to the development of the standard of living (Jani, Marchand, & Hogland, 2014). As showed by previous studies (Quaghebeur et al., 2013), the fine fractions from landfill-mined waste might contain high concentrations of certain metals, offering attractiveness for feasible material recovery. Special attention should be paid to critical and rare earth metals, as their prices can reach high levels (Bhatnagar et al., 2017). However, the recovery of rare earth metals from landfilled waste could be used as an additional source of revenue sometimes and not as one of the main drivers for LFM, since these metals are used in very specific applications, which were not predominantly disposed of in MSW landfills and, hence, their primary recovery route for recycling might remain to be the separate collection of the products in which they were used.

Rare earth elements (REEs), platinum group metals (PGMs), Li, In, Co and Sb have been identified as high risk of supply shortage and increased impact on the economy (Hislop, 2011 in Gutiérrez-Gutiérrez et al., 2015).

Concentrations of critical metals, such as Co (11 mg/kg), Ga (2.2 mg/kg), Nb (2.5 mg/kg), Ta (1.2 mg/kg), and W (56 mg/kg); REEs, such as Gd (0.75 mg/kg), Nd (7.26 mg/kg), Pr (1.9 mg/kg) and Y (7.85 mg/kg); PGMs, such as Pt (59 µg/kg), Rh (0.092 µg/kg) and Ru (0.5 µg/kg); Ag (5.3 mg/kg) and Au (0.4 mg/kg) have been found present in MSW (Morf et al., 2013). Low recycling rates of REEs, Sb, In, Co and Li have been also reported in Graedel et al., 2011. However, the observed concentrations are far below the cut-off grades which are in the range of several wt% REE oxides, for example (Lehmann, 2014).

Furthermore, the proportion of REEs in the fine fraction reported by Burlakovs, Kriipsalu et al., 2016 between four sites did not present a significant variation; being Ce, La, Nd and Y the elements found in higher amounts with around 35.5 wt.%, 19 wt.%, 18 wt.% and 9 wt.%, respectively, with respect to the total REEs amount. Ce, Nd, Li, Sb and Co were the most abundant metals in the excavated waste reported by Gutiérrez-Gutiérrez et al., 2015 and did not present significant variations between the studied landfills either. Li had the greatest concentration range of all examined critical metals (11.17-27.66 mg/kg), followed by Co (8.72-14.14 mg/kg), Sb (6.40-15.15 mg/kg) and In (0.04-0.10 mg/kg) (Gutiérrez-Gutiérrez et al., 2015). The range concentrations of Ce and Nd were 13.85-25.20 mg/kg and 8.34-11.75 mg/kg, respectively (Gutiérrez-Gutiérrez et al., 2015). Nevertheless, the amounts of Cu, Ag and Au found were highly variable between different sites and the PGMs concentrations, except for Pd (0.41-0.77 mg/kg), were found low (Gutiérrez-Gutiérrez et al., 2015).

The recovery of metals (critical metals and other metals such as Al, Cu, Ag and Au) together with other materials of value (e.g. recyclables and RDF) may result in a feasible business model for LFM (Gutiérrez-Gutiérrez et al., 2015). According to Van Vossen & Prent, 2013, an amount of 2.5 vol.%. metals recovery could reduce the costs of landfill mining about 20%, which could be raised to 30-40% by future prices rises due to increasing raw materials scarcity. Thus, the potential of the fine fractions as secondary source of important metals is emphasized by the considerable amounts of them that can be found in the fines (Bhatnagar et al., 2017).

4. CONCLUSIONS

The results from the previous investigations reveal that around 40-80 wt.% of the total excavated material out of a landfill correspond to fine fractions. Each landfill site has its own potential regarding LFM or ELFM. Factors such as the age and type of the landfill, as well as its location and operation procedures might have a relevant impact on their content and valorization potential.

According to previous studies the amount of fine particles to be obtained in a LFM project mostly depends on the excavation and processing techniques, the age and type of the waste and the selected cut-off diameter to define a certain particle size as upper limit for the fines fraction.

Fine fractions can be considered as a relevant source of metals and calorific fractions, as well as a fraction suitable for inert and soil-like material recovery. This situation makes their recuperation from landfills interesting; since old landfills are not just a potential source for such elements, but this might also be a decisive factor to achieve economic feasibility in LFM and ELFM projects.

Moisture, organic content and other physico-chemical properties are interrelated parameters of critical relevance, since processing routes and possible end uses for the fine fractions will depend on their quantities to a certain extent.

Drying of the fine fractions could: i) reduce the amount of surface defilements; increasing the quality of the recyclable materials and raising the efficiency of sorting processes, especially for the sensor-based sorting technologies, such as near infrared (NIR) and color recognition (VIS), ii) enable a more efficient and precise particle size classification in the screening and sieving processes, iii) decrease the total amount of material and material flowrate to be processes and, perhaps, transported and iv) raise the calorific value.

The particle size will be a key parameter in LFM and ELFM future investigations for the separation of the fine fractions into exploitable resources and the minimization of the material to, if the case, be sent back to re-landfilling. To achieve this, the fine fractions may be classified into certain particle size ranges, selected according to the results of the material characterization and particle size distribution during the exploration phase of the project, to determine the cut-off diameter size for the fine fractions and enable more efficient material recovery, for different purposes (e.g. recycling and alternative fuel), and recuperation of soil-like and inert materials in the corresponding processing techniques (e.g. density, magnetic and eddy-current separators, among others).

Much care needs to be taken when comparing information between different investigations, since there are many factors, such as characterization conditions and procedures, laboratory analyses and followed standards, age of the waste material, defined particle size for the fines fraction, among others, that might play an important role during their execution and may differ significantly between investigations.

The implementation of different approaches for the material characterization of waste remains to be one of the crucial challenges for the elaboration of comparable and accurate compiled studies.

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4 POTENTIAL OF FINE FRACTIONS FOR MATERIAL AND ENERGY RECOVERY

Scientific article no. 3: “Potential and Main Technological Challenges for Material and Energy Recovery from Fine Fractions of Landfill Mining: A Critical Review”

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Annotation on my personal contribution to this scientific article:

According to the previously gathered information for the scientific article no. 2 and its findings, and after doing a further review of previous LFM studies focused on the treatment and valorization of the fine fractions, I identified and proposed potential WtM and WtE valorization schemes for the fine fractions. I wrote most of the article in consultation with Daniel Höllen and Roland Pomberger. The article was reviewed by all 3 authors and the revision was done by me.

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

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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

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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-

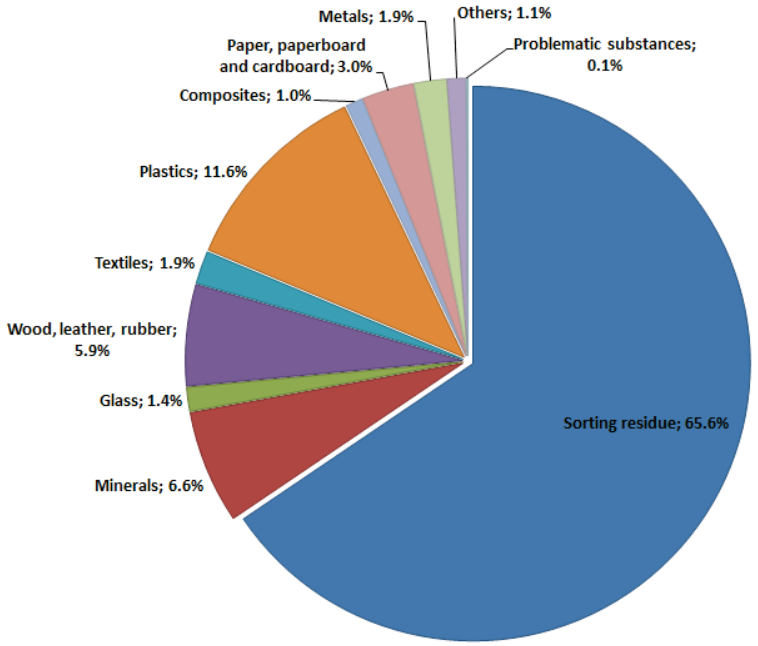

FIGURE 1: Composition of fraction <40 mm of landfill-mined material from a MSW landfill in Austria (modified from Wolfsberger et al., 2015).

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-

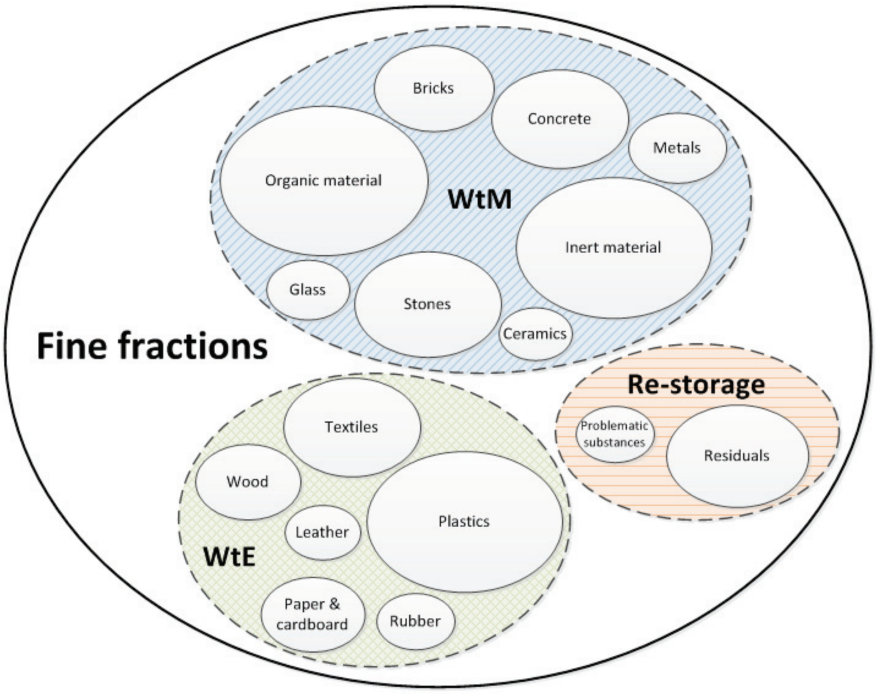

FIGURE 2: Potential of the fine fractions for WtE and WtM.

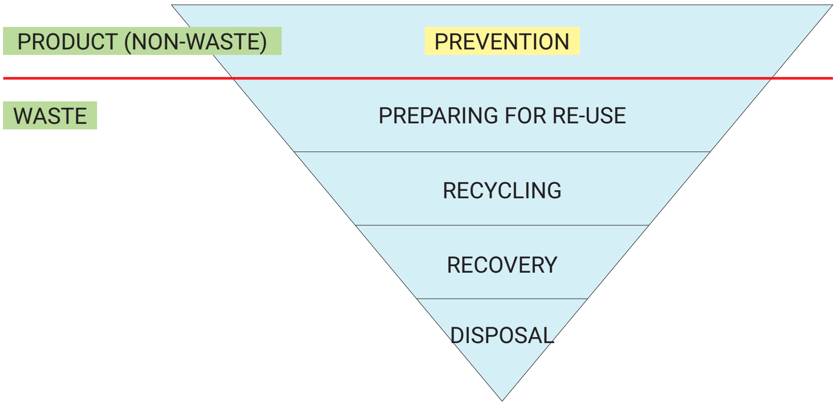

FIGURE 3: Waste management hierarchy (European Commission).

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-

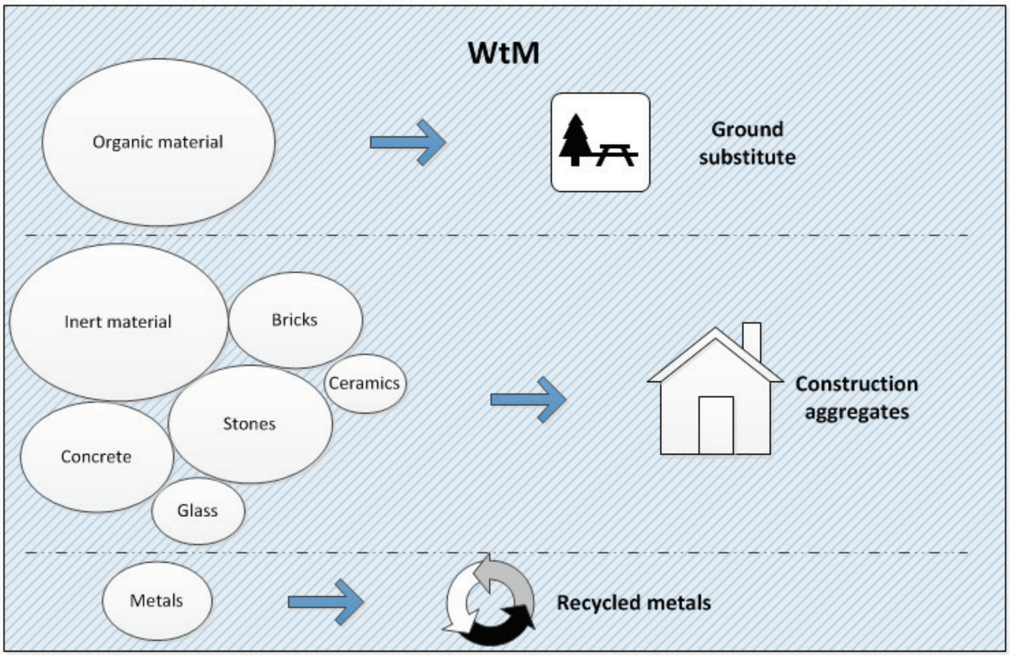

FIGURE 4: Material recovery from organic and inert fractions of LFM fine fractions.

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

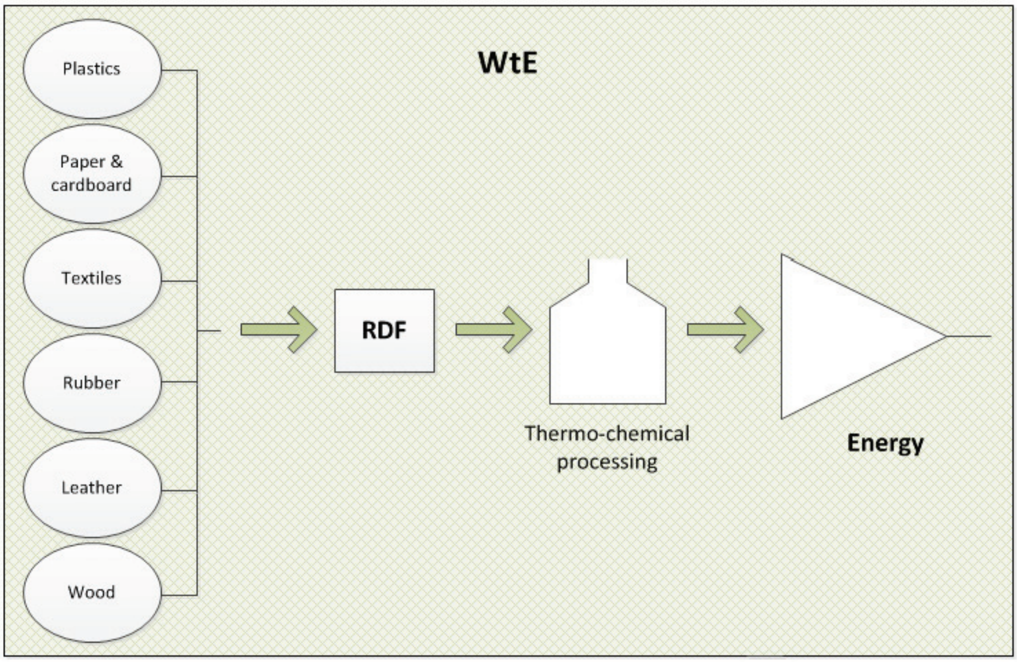

FIGURE 5: Energy recovery from calorific fractions of LFM fine fractions.

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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5 MONT-SAINT-GUIBERT CASE STUDY: MATERIAL EXCAVATION AND MECHANICAL PRE-PROCESSING

Scientific article no. 4: “Characterization of Landfill Mining Material after Ballistic Separation to Evaluate Material and Energy Recovery Potential”

Garcia Lopez, C., Ni, A., **Hernández Parrodi, J.C.**, Küppers, B., Raulf, K., Pretz, T., 2019. Characterization of Landfill Mining Material after Ballistic Separation to Evaluate Material and Energy Recovery Potential. Detritus 8 (1), 5–23. 10.31025/2611-4135/2019.13780.

Annotation on my personal contribution to this scientific article:

In collaboration with all involved authors I conceptualized, organized and managed the tests carried out for this article. The activities onsite were executed by Cristina García López, Bastian Küppers and me, as well as in collaboration with the staff from the landfill site and the company which supplied the ballistic separator. The samples of the pre-processed material with the ballistic separator were taken by Cristina García López, Bastian Küppers and me. I conducted the particle size reduction of the coarse fractions onsite and collaborated with Cristina García López, Anita Ni and Bastian Küppers to perform the characterization of the coarse fractions. In addition, I was involved in the analysis and interpretation of the results in consultation with Karoline Raulf and Thomas Pretz, as well as in the writing of the whole article. All involved authors carried out the review of the article and I assisted Cristina García López in the revision.

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CHARACTERIZATION OF LANDFILL MINING MATERIAL AFTER BALLISTIC SEPARATION TO EVALUATE MATERIAL AND ENERGY RECOVERY POTENTIAL

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ABSTRACT

For decades, ballistic separators have been used in Europe as a means of sorting waste to separate mixed waste material streams at material recovery facilities and municipal solid waste treatment plants. Currently, with the growing need to remediate landfill sites, ballistic separators can be employed to recover calorific fractions from excavated landfill material within the framework of enhanced landfill mining. Ballistic separators provide multiple separation steps in one machine: they sort flat two-dimensional materials from rigid three-dimensional materials, while the material is screened to a selected particle size at the same time. The present study shows the results obtained during an investigation performed at the landfill in Mont-Saint-Guibert, Belgium. The main objectives were to acquire first-hand information regarding the efficiency of the ballistic separator in relation to processing old and untreated landfilled material and to study the potential of the landfill as a reservoir of secondary resources. The excavated material was processed through a pre-treatment chain of steps, including material classification and separation, as well as particle size reduction. As a first step, the material was processed with a ballistic separator using two different mesh sizes, 200 mm and 90 mm. Subsequently, the performance of the separator in question was evaluated, especially regarding its effectiveness in the production of refuse derived fuel. The two-dimensional flow was characterized by combustible materials from municipal solid waste and the three-dimensional by construction and demolition waste. As a result, 46% (dry basis) of the input material were fines particles <20 mm, 3% had a calorific value of 22.4 MJ kg^{-1}, 1% 16.0 MJ kg^{-1} and approximately 1% were magnetic metals that could be recovered by mechanical processes. The results of processing and valorising the potential resources disposed in landfills are essential for the implementation of enhanced landfill mining since revenues from material and energy recovery could contribute to the economic feasibility of the project.

1. INTRODUCTION

As the global demand for raw materials rises, while the availability of natural resources remains limited, alternative sources of materials demand investigation and, therefore, new techniques need to be developed in order to maximize the use of existing materials. A political framework to tackle these challenges was set by the 2020 Strategy of the European Union (EU). This strategy serves as the basis for the 7th Environment Action Programme, which seeks to develop a sustainable, low-carbon and resource-efficient economy where waste is turned into a resource (European Parliament, 2013). Regarding historic waste, it is of major interest to identify the potential and examine which secondary resources could be recovered from the existing 150,000 to 500,000 landfills that are estimated to be located in the EU (Hogland et al., 2010). This subject is investigated in enhanced landfill mining (ELFM) projects, which aim for “the safe conditioning, excavation and integrated valorisation of (historic and/or future) landfilled waste streams, both as materials (Waste-to-Material, WtM) and energy recovery (Waste-to-Energy, WtE), using innovative transformation technologies and respecting the most stringent social and ecological criteria” (Jones et al., 2013). ELFM contributes to create a circular economy and to reduce the EU’s dependency on imports of raw materials, driven by the goals of reclaiming land, re-

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gaining landfill capacity and protecting groundwater, as has previously been achieved by landfill mining (LFM) projects (Hermann et al., 2014; Hernández Parrodi et al., 2018a).

This study focuses on the characterization of landfilled material that was directly processed with a ballistic separator after excavation. Figure 1 shows the working principle of a ballistic separator, which is a standard processing equipment, normally installed in packaging waste treatment plants before sensor-based sorting or after in-feed with subsequent drum screen. Due to the inclination and upward movement of the paddles, three-dimensional (3D) materials (heavy, hard and round particles) move downwards and are separated from the two-dimensional (2D) materials (lighter and soft particles), such as plastics, paper and textiles, which are collected at the top end of the paddles. A third output stream, the under-sieve fraction, is produced due to the screening property of the paddles. The latter can be varied by adjusting the screen of the paddles according to a certain particle size. Material characteristics, such as weight, form, size and elasticity, can influence the movement of the particles and can, therefore, affect the sorting efficiency of the equipment.

A bottom-up approach, in contrast to a top-down approach analysing historical data (Bhatnagar et al., 2017), was chosen in this study. Especially since most older landfill sites did not register the type and amount of material deposited during their active phase (Jones et al., 2013). However, landfilled materials are heterogeneous waste streams that need to be separated and treated before they can be recovered (Quaghebeur et al., 2013). Previous studies provide information on the applicability of full-scale and state-of-the-art technology used currently in waste-treatment plants (García López et al., 2018; Kaartinen et al., 2013; Maul & Pretz, 2016).

The novelty of this case study is the use of a ballistic separator as the first step of the mechanical process prior to shredding. This method allows the recuperation of fractions that are suitable for the production of refuse derived fuel (RDF) with a high heating value in its original size, in addition to other valuable materials, such as inert, glass and metallic materials.

Landfilled waste from which RDF might be produced includes plastics, paper, wood and textiles (calorific fractions). In addition, metals, glass and perhaps mineral and organic materials could be recovered (Kaartinen et al., 2013; Quaghebeur et al., 2013). The material composition of landfill sites varies according to different factors, such as the time of deposition, the type of stored waste, the meteorological and hydrological conditions of the site, and the collection area, since waste composition is influenced by population density, consumer behaviour and waste-sorting habits (Quaghebeur et al., 2013; Wolfsberger et al., 2015a). Therefore, a holistic characterization of the landfilled waste contributes to assessing the suitability of a site for ELFM, which is determined by the share of usable recyclables from the excavated waste, among others, and to predict the revenue and costs of an ELFM project (Hermann et al., 2014).

The purpose of this study is to evaluate the performance of the ballistic separator "STT 6000"-STADLER® Anlagenbau GmbH" with landfilled material. This evaluation was achieved by characterizing each output stream of the ballistic separator. The materials composing these streams were identified by manual sorting and were subjected to laboratory analyses, such as moisture content, particle-size distribution (PSD), calorific value and ash content, to obtain qualitative and quantitative information and determine the suitability of the calorific fractions for the production of RDF.

2. MATERIALS AND METHODS

2.1 Site description

The examined landfill site is located in the municipality of Mont-Saint-Guibert (MSG) in the province of Walloon Bravant, Belgium. This site was established on a former sand

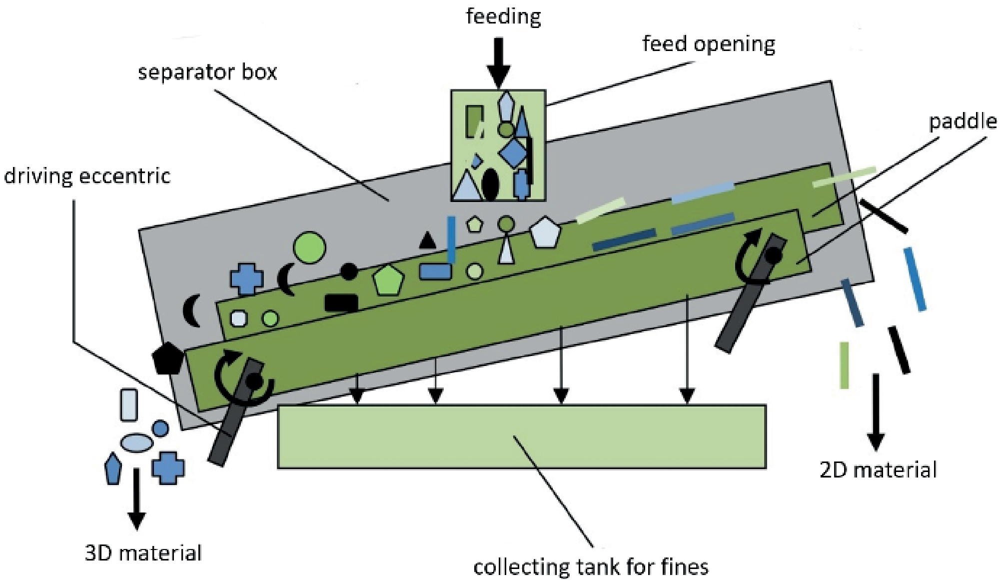


FIGURE 1: Schematic diagram of a ballistic separator (adopted from Martens & Goldmann, 2016).

quarry and has served as one of the main disposal sites of municipal solid waste (MSW), non-hazardous industrial waste and construction and demolition waste (CDW) since 1958 (Bureau d´études greisch, 2002). The site covers an area of approximately 44 ha, of which 26 ha belong to the most recent part and 2 ha to the oldest part. The oldest part of the site has no bottom liner and, nowadays, the biogas collection system has been removed, while the leachate collection system is still in place and operational. The present investigation was carried out in the old part of the landfill, which has an estimated depth between 30 m and 60 m and where at least 5.7 million m^3 of waste were deposited between 1958 and 1985 (Hernández Parrodi et al., 2018b).

In September 2017, before the excavation, a geophysical exploration was performed in an area of approximately 2150 m$^{2.}$ Using electromagnetic induction, the depth of the cover layer and the soil properties were estimated. Based on the results of the electrical conductivity, the area was then divided into four batches. This paper focusses only on batch 1. A future publication will show the results of all four batches.

As shown in Figure 2, the waste was covered by a clay layer with a thickness of about 4 m. This layer was removed in order to keep it separated from the landfill waste. The processed pit was 5 m long, 5 m wide and 4 m deep; a total volume of 130 m^3 was excavated and treated. During the excavation, a layering of different types of materials was observed. From top to bottom: 4 m cover layer, 2 m CDW and 2 m MSW. For the extraction of the buried material, an excavator with a toothed digging-type bucket was employed, while for the manipulation of the excavated material a wheel loader was used. The weight of the material was measured with a weighing bridge (resolution of 50 kg).

2.2 Mechanical processing and sampling campaign

After the excavation, the material was directly fed into the ballistic separator "STT 6000", the specifications of which are given in the Appendix. The motivation for the choice of this specific equipment was the following: i) the conglomerates of the input material would be loosened up due to the agitation (crankshaft eccentricity) on the screen deck, ii) its availability for treating CDW (Sigmund, 2018), iii) no pre-shredding of the input material is needed (saving the wear and energy on the shredders for the infeed material), iv) sorting large items increases sorting quality (large parts can be removed in one piece), v) saving of space on the site due to the separation of 3 fractions in one step (vs. a drum type, by which only particle size can be sorted), and vi) its robust design. Thus, these characteristics could lead to better sorting processes (enhanced mechanical treatment) with respect to effectiveness, wear and energy consumption. Even if previous studies recommend low moisture content (<15%) for an effective sorting process (Giani et al., 2016; Martens & Goldmann, 2016), this study was performed without drying the material prior to the processing.

FIGURE 2: Excavation at the Mont Saint Guibert Landfill, Belgium.

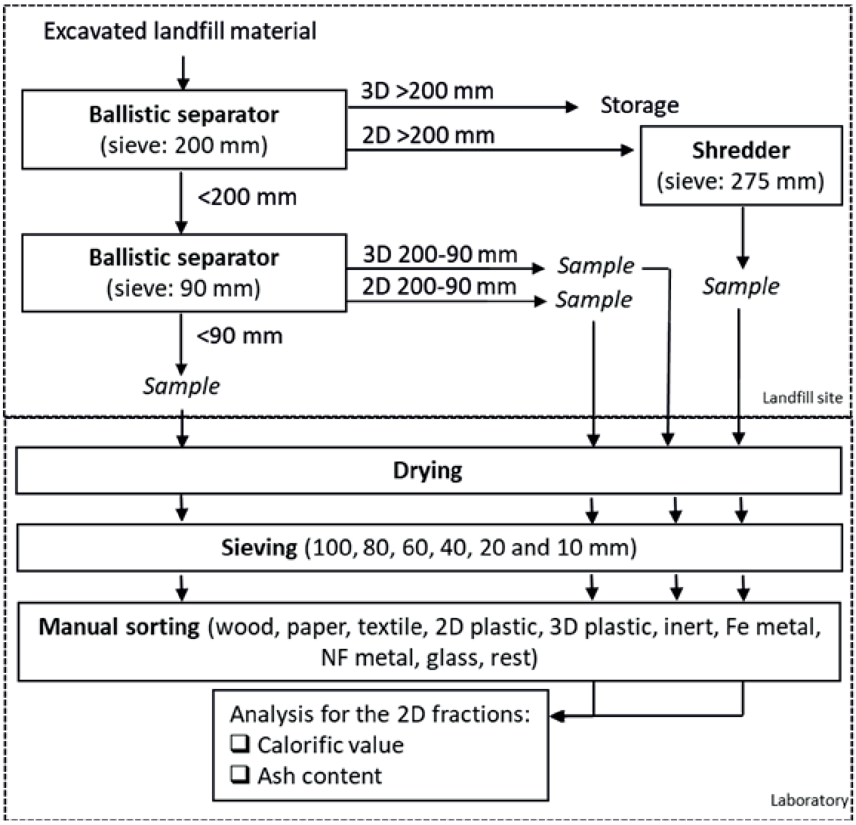


FIGURE 3: Scheme of the mechanical pretreatment, sampling campaign and methodology used in the laboratory.

The landfilled material was first sieved with a mesh size of 200 mm and subsequently with a mesh size of 90 mm, as can be seen in Figure 3. The output “2D >200 mm” was fed into a shredder (sieve: 275 mm) to reduce the particle size down to <275 mm; hereafter, this output stream is referred to as “2D <275 mm”.

The sampling campaign followed the same methodology as in the case study in Halbenrain (García López et al., 2018), based on the German Directives (LAGA PN 78; LAGA PN 98). The “3D >200 mm” output stream was not sampled; instead, all the output material was sorted in situ into different categories (Table 1). Moreover, 60 m^3 of the obtained fraction <200 mm were subsequently processed with the ballistic separator with a mesh size of 90 mm, from which 3 additional output streams were obtained: 2D 200-90 mm, 3D 200-90 mm and <90 mm.

The following numbers of samples were taken exclusively during the mechanical treatment and were adapted to the time of the process to achieve the maximum level of representation: i) 2D <275 mm, 8 samples (n=8), summing to 132 kg, ii) 2D 200-90 mm, 9 samples (n=9), summing to 63 kg, iii) 3D 200-90 mm, 7 samples (n=7),

TABLE 1: Classification of the landfilled material by categories.

Category	Material	Age of site (as of 2018)
I	Wood	All types of wood
II	Paper	Paper, cardboard, composite carton
III	Textile	All types of textiles
IV	Plastic 2D	Bags, foils
V	Plastic 3D	PP, PET, HDPE, LDPE, PVC, PS, others
VI	Fe metals	Iron
VII	NFe metals	Non ferrous metals: copper, aluminium, lead, others
VIII	Inert	Mineral fraction (stones), ceramic
IX	Glass	Colorless glass, green glass, brown glass, others
X	Rest	Rubber, foam, EPS, silicone, melted plastics, sandpaper, hazardous waste (e.g. sanitary material), unidentified, composites
XI	Fines	Particles < 20 mm

summing to 154 kg and iv) <90 mm, 12 samples (n=12), summing to 116 kg. All the figures with fluctuations given in this study are based on the corresponding number of samples. The samples were further characterized in the Department of Processing and Recycling at the RWTH Aachen University.

2.3 Characterization of landfill mining material

2.3.1 Moisture content and particle size distribution

Based on the DIN CEN/TS 15414-1 all samples were dried but at a reduced temperature of 75°C to prevent plastics from melting, which can happen at higher temperatures.

After drying, the samples from the output streams 3D 200-90 mm, 2D 200-90 mm, <90 mm were sieved with a drum sieve and a box sieve at the Department of Processing and Recycling (RWTH Aachen University), except for the ones from 2D <275 mm, which did not provide realistic information regarding the size of the original material. As a result, seven particle size fractions were generated: 200-100 mm, 100-80 mm, 80-60 mm, 60-40 mm, 40-20 mm, 20-10mm and <10 mm.

2.3.2 Material composition by output stream

All the particle size fractions >20 mm from 2D <275 mm, 2D 200-90 mm, 3D 200-90 mm and <90 mm were sorted manually into eleven categories, listed in Table 1. There is no category for organic waste (food scraps, green waste, etc.) because they were not distinguishable after at least 15 years inside the landfill. It is likely that the organic material was degraded to soil-like material (Quaghebeur et al., 2013). At this point, it must be mentioned that no pure and clean materials can be obtained by manual sorting without washing or using other pretreatment due to surface defilement and material agglomeration.

2.3.3 Calorific value and ash content

Such characteristics as calorific value, amount of organic carbon, total carbon, ash content, and hydrogen and nitrogen contents are needed to be measured to assess the efficiency for WtE applications (Quaghebeur et al., 2013). In this case, only the gross calorific value (GCV) and the ash content were determined. These values give information about the recoverable energy and amount of residue produced in the combustion process (Kuchta, Hobohm, & Flamme, 2017). Before conducting the analysis, several mills (hammer mill, disc mill and cutting mill) were used to reduce the size of the particles down to 1 mm. After the particle size reduction of each category in each sample, the GCV was determined according to the DIN 51900-1 and the ash content based on DIN EN 15403. The measurements were only conducted for the 2D output fractions (2D 200-90 mm and 2D <275 mm), which were estimated to have a high heating value. Metals and glass were assumed to have a GCV of 0 J/kg and an ash content of 100%.

3. RESULTS AND DISCUSSION

3.1 Moisture content and particle size distribution

The moisture content landfilled material plays an important role when considering the material processing (Hull et al., 2005). Previous experiences include that moisture contained in excavated waste did not impede its processability, but it might have an impact on the processing efficiency (Kaartinen et al., 2013). Drying could (i) reduce the amount of surface defilement; increase both the quality of the recyclable materials and the efficiency of sorting processes, (ii) enable a more efficient and precise particle size classification in the screening and sieving processes, (iii) decrease the total amount of material to be processed and perhaps transported and (iv) raise the calorific value (Hernández Parrodi et al., 2018a).

The fluctuations in the moisture content within the samples of every output stream are represented in Figure 4. The similar moisture contents of 2D <275 mm and 2D 200-90 mm, with averages of 31% and 32% respectively, allow a first estimation about their composition, which is described in detail in the section "3.2. Material composition". The output "<90 mm" is characterized by a slightly lower average moisture content of 28%, while "3D 200-90" mm contains considerably less water, showing an average of 12%. The latter correlates with the low capacity to hold water of materials usually found in the 3D output stream of ballistic separators, such as stones, metals, glass, rubber and wood.

It has been reported that the moisture content and amount of organic matter are interrelated and decrease with the age of the waste due to microbiological activity (Quaghebeur et al., 2013). Dating back to the 1960s and 1970s, the investigated waste from MSG can be considered as old. Nevertheless, the amount of water is still notable, with a range of 9-41%, which might be explained by the thick layer of clay used as cover material and the type of waste landfilled. More permeable material, such as compost, leads to higher degradation rates and thus faster water reduction.

Due to this moisture, fine particles likely adhere to surfaces and larger particles which may lead to an increased share of the fine fraction after drying (Kaartinen et al., 2013) .Combined with the subsequent sieving, this may contribute to the reduction of surface defilement and as a consequence, compliance with the requirements for other waste treatments, e.g., sensor-based sorting if considered for further processing.

Drying the material is an operational cost but can reduce the total mass being transported and fed into the mechanical processing; hence, the throughput might be increased and transportation costs reduced. Other effects of drying are an increase in the CV and more effective sieving results.

Figure 5 illustrates the total mass (dm%) by particle size (mm) in each sieved output stream from which it can be deduced that a dried sample of landfilled material contains more fine particles than it did under humid conditions. After drying, 51% of the output stream "2D 200-90 mm" is smaller than 80 mm, even though it was first classified as >90 mm by the sieve of the ballistic separator. Moreover, fines <10 mm in this output stream make up 30%, which is almost as high as the share of particles >100 mm (35%).

For the "3D 200-90 mm", 28% is <80 mm. This statement can only be made with some reservations, since

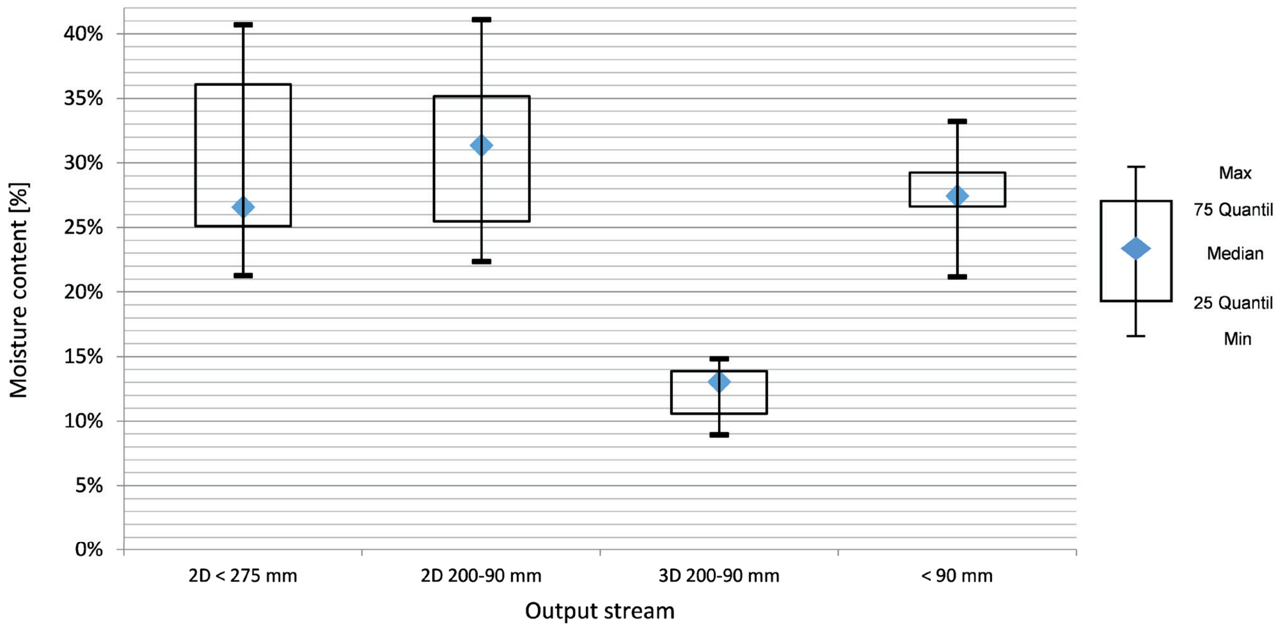
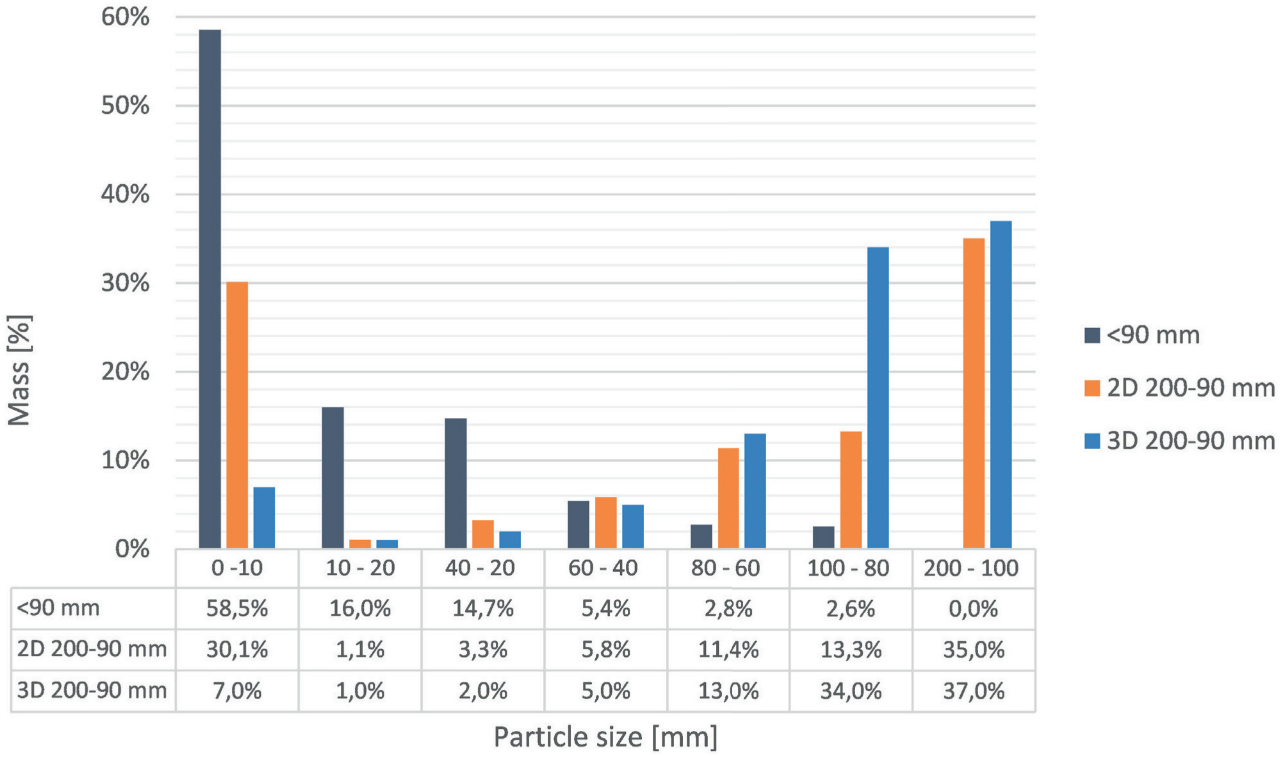


FIGURE 4: Fluctuations in the moisture content by the output stream of the ballistic separator. Number of samples shown, n=8, n=9, n=7, n=12.



	0 -10	10 - 20	40 - 20	60 - 40	80 - 60	100 - 80	200 - 100
<90 mm	58,5%	16,0%	14,7%	5,4%	2,8%	2,6%	0,0%
2D 200-90 mm	30,1%	1,1%	3,3%	5,8%	11,4%	13,3%	35,0%
3D 200-90 mm	7,0%	1,0%	2,0%	5,0%	13,0%	34,0%	37,0%

FIGURE 5: Distribution of the total mass (dm%) by particle size in each sieved output stream of the ballistic separator STT 6000 using landfilled waste.

some bricks broke during the sieving in the drum sieve, especially in the first run with a mesh size of 100 mm. This means that the actual throughput at particle size 100 mm is lower than indicated in Figure 6 and that the particle-size fraction 200-100 mm composes more than one third of the whole output stream "3D 200-90 mm". Besides, more fines than those originally contained in the samples are generated due to abrasion processes while sieving the material.

In addition, there is a concentration of material in the smaller particle size fractions: 34% of "2D 200-90 mm" is < 40 mm and 30% is <10 mm. Regarding the output stream <90 mm this observation is more significant, with values of 90% and 59%, respectively.

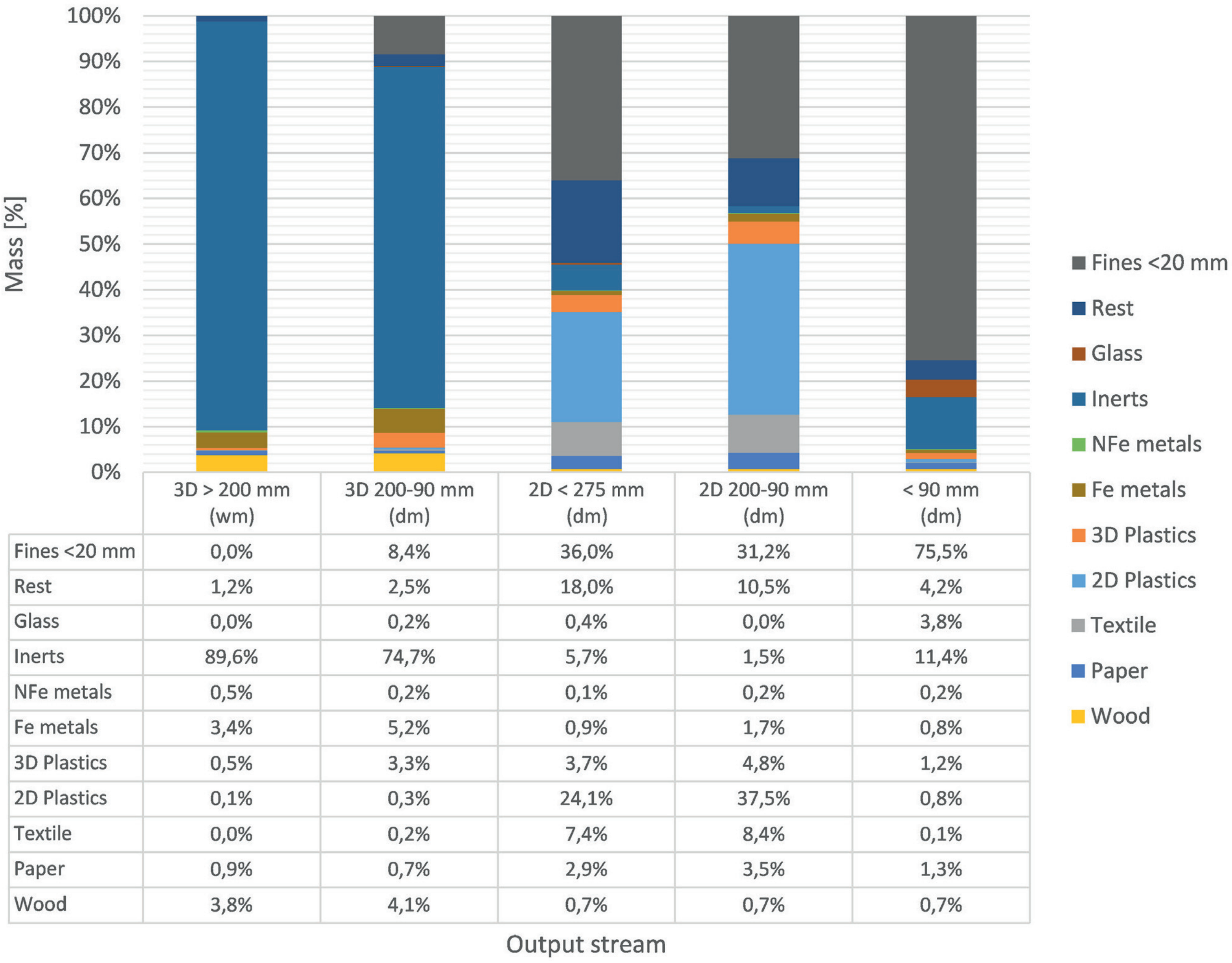
In line with the above-described findings, the moisture content of all samples varies between 9 and 41% and on the average makes up for almost a third of the RDF potential fractions. The PSD reveals a high percentage of fine material, not only in the output stream <90 mm but in all outputs due to the large amount of impurities found between the large particles, which are separated by the drying process.

3.2 Material composition

The excavated waste from MSG (batch 1) consisted of three main categories: inert, fines and plastics. In this study, all particles with a particle size <20 mm are defined as fines. Figure 6 gives an overview of the material distribution in all the output streams generated by the ballistic separator. As expected, most fines are found in the output stream <90 mm, additionally both, 2D >200 mm and 2D 200-90 mm, show considerable amounts of fines. Inert material is concentrated in the 3D output streams (3D >200 mm and 3D 200-90 mm). The ferrous metals (Fe metals) are mainly found in the 3D output streams: 3% in the >200 mm and 5% in the 200-90 mm output, as well as wood with 4% in the both 3D output streams. It must be noted that the mass percentages of “3D >200 mm” are given on a wet matter (wm) basis, while the other streams flows refer to dry matter (dm). Detailed figures (Fig. A.1-3) with the average values of the masses by particle size in each output can be found in the Appendix.

3.2.1 Output stream 3D 200-90 mm

The box whisker diagram in Figure 7 illustrates that the inert fraction is by far the largest with a median of 75%, while the other fractions all range below 10% with tendencies toward 0%; the shares of the categories paper, textile, 2D plastics, Non Ferrous (NFe) metals and glass are less than 1%. The same explanation as above may be considered for the high amount of inert material: the upper layer of the pit consisted of CDW. The second largest fraction is that of fines (8%), followed by Fe metals and wood, 5% and 4% respectively. Regarding Fe metals and wood, it was observed that half of the samples contained compounds of both materials in the fractions 60-40 and 40-20 mm. As the magnetic forces of a magnetic separator attract ferrous materials, wood parts containing nails were categorized as Fe metals. On the other hand, a large piece of wood (100-80 mm) with nails was identified and classified as wood. Another compound found was wood with 3D plastic.



	3D > 200 mm (wm)	3D 200-90 mm (dm)	2D < 275 mm (dm)	2D 200-90 mm (dm)	< 90 mm (dm)
Fines <20 mm	0,0%	8,4%	36,0%	31,2%	75,5%
Rest	1,2%	2,5%	18,0%	10,5%	4,2%
Glass	0,0%	0,2%	0,4%	0,0%	3,8%
Inerts	89,6%	74,7%	5,7%	1,5%	11,4%
NFe metals	0,5%	0,2%	0,1%	0,2%	0,2%
Fe metals	3,4%	5,2%	0,9%	1,7%	0,8%
3D Plastics	0,5%	3,3%	3,7%	4,8%	1,2%
2D Plastics	0,1%	0,3%	24,1%	37,5%	0,8%
Textile	0,0%	0,2%	7,4%	8,4%	0,1%
Paper	0,9%	0,7%	2,9%	3,5%	1,3%
Wood	3,8%	4,1%	0,7%	0,7%	0,7%

FIGURE 6: Composition of all output streams by categories.

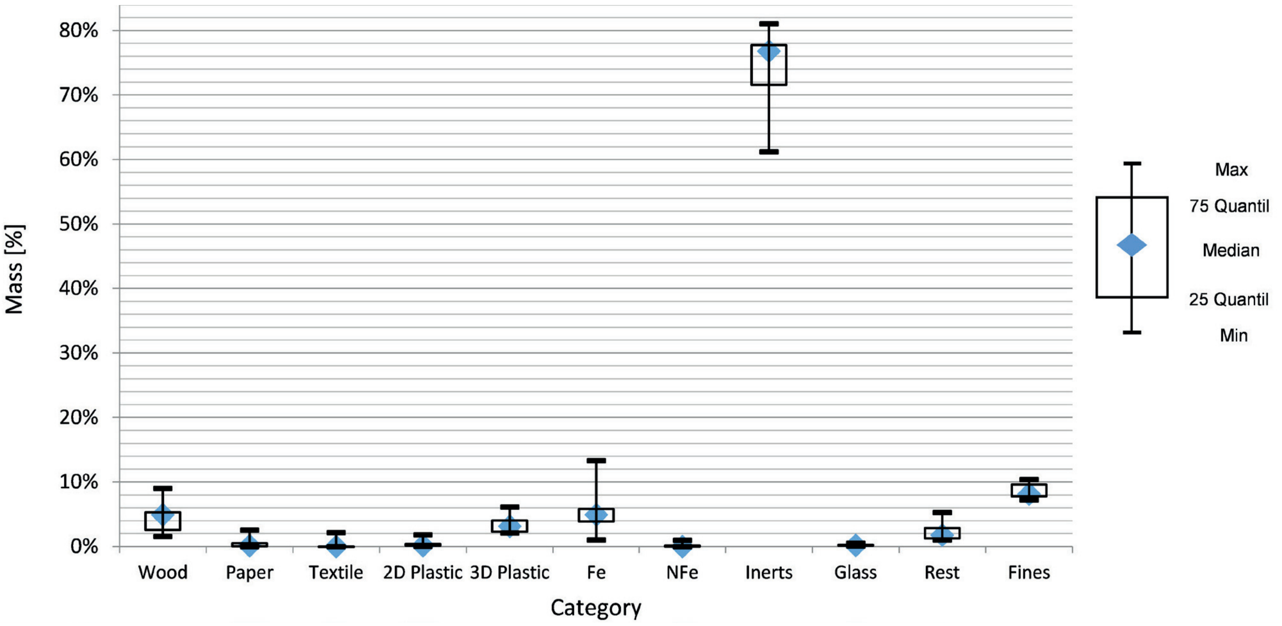


FIGURE 7: Output "3D 200-90 mm": fluctuations in the material composition, dm % (n=7).

The fluctuations indicate that the samples do not differ strongly from each other. The largest variations are observed in the categories wood, Fe metals and inert material, which also correspond to those obtained in previous LFM investigations.

Figure 8 represents the composition of each particle size fraction indicating its weight as it relates to the total weight of the output "3D 200-90 mm". The two larger coarse fractions make up most of the material, 37% and 34%, but breaking and abrasion in the drum sieve have affected the PSD distribution. Wood presented in the output "3D 200-90 mm" is distributed equally between the three larger particle size fractions, whereas most iron particles are counted in the 100-80 mm fraction (2%). The low quantity of glass (0.2%) might be explained by the fact that glass is likely to break and pass the sieve, both when previously transported and landfilled and during the excavation and mechanical stress in the ballistic separator, finally ending in the output stream <90 mm.

Looking to further processing steps, the enrichment of one material by sieving could result in difficulty due to similar distribution curves. Therefore, different sorting treatments such as magnetic separation, sensor-based separation (Beel, 2017; Martens & Goldmann, 2016), or float-sink separation (Bauer et al., 2018; Kranzinger et al., 2017) could be considered. Generally, the composition resembles the output "3D >200 mm" although it shows an increased number of fines generated in the PSD process (particle breakage and the drying process). Hence, the ballistic separator meets the expectations for enrichment of 3D materials.

3.2.2 Output stream 2D <275 mm

As shown in Figure 9, the output stream 2D <275 mm has a heterogeneous composition in comparison with 3D 200-90 mm, where the fine fraction (<20 mm) holds the largest share with 36% of the total. These fines are mainly composed of a mix of 2D plastics and soil-like material that may have been generated during the shredding process and due to the high detention time inside the shredder (Figure 10). To prevent losing this part of the combustibles in the fine fraction, sieving with a mesh size of 10 or 5 mm is suggested. Moreover, a considerable number of particles (particle size approximately <3 mm and smaller) were attracted by the magnet, being magnetic soil-like. Comparable findings are also described by Quaghebeur et al., 2013, where the amount of metallic iron in the magnetic fraction was between 8 and 9%.

The second-largest fraction is made up by 2D plastics with an average share of 24%, followed by Rest with 18%. Many particles categorized as Rest during the sorting process are compounds, such as carpets and nappies. They are mainly made of plastic, textile and cellulose, thus this category may be considered as a highly calorific fraction. Another compound that was mainly present in the output stream "2D <275 mm" consists of cables. If the 2D and 3D plastics, Rest, wood, paper and textile are considered highly calorific materials, 57% of the total mass has RDF potential. However, wood is insignificant with less than 1%. The same applies to glass and both Fe and NFe metals. Metals could not be separated completely due to attached pieces of plastic, mostly two-dimensional, textile or other materials.

3.2.3 Output stream 2D 200-90 mm

As it can be seen in Figure 11, the grain-size fractions >60 mm in the 2D 200-90 mm flow are especially rich in plastic foils (>45%). As expected, the main component of this flow are 2D plastics with an average content of 41% (Figure 12). In contrast, 32% were fines (<20 mm), which may reduce the RDF potential drastically. However, the categories Rest and wood could contribute to increase the

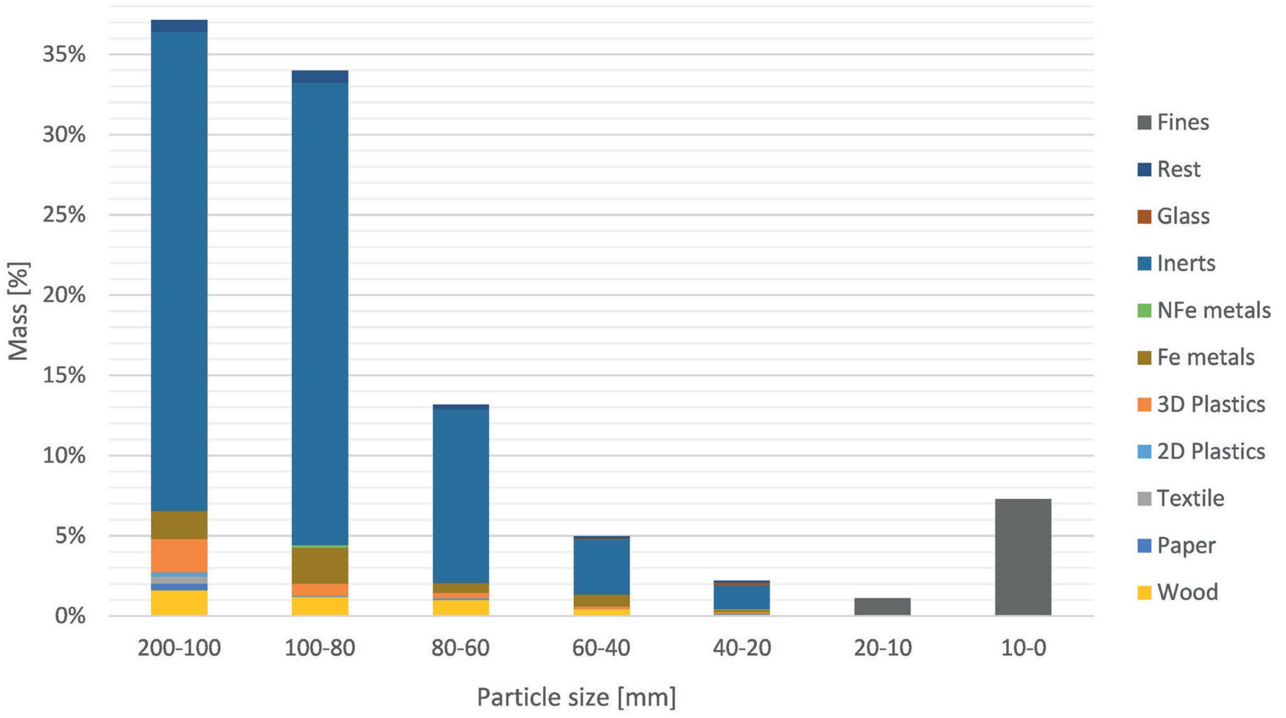


FIGURE 8: Material composition of the output stream ”3D 200-90 mm” by particle size.

calorific value with a share of 7% and 6% respectively, since they are considered combustible materials.

Furthermore, it can be said that fraction 40-20 mm has a very heterogeneous composition consisting of all materials except glass, while the other sorted particle sizes are characterized by 2D plastics as the main component.

All inert material can be discharged by sieving with a mesh size of 80 mm, as shown in Figure 15. Apart from wood and fines, all other categories show similar distribution curves, so sieving alone will not be suitable for the enrichment of single categories as it is also the case for 3D 200-90 mm. Regarding the heterogeneous composition of both 2D streams compared to the 3D stream characterized by CDW, it can be deduced that the composition of this stream consists mainly of MSW with a high content of potential combustibles.

3.2.4 Output stream <90 mm

Most of the output stream (75%) consisted of fines <20 mm, Figures 13 and 14. These were not sorted manually, but as a general observation the particle sizes between 20 and 10 mm consisted mainly of glass and those <10 mm of soil-like material, comparable to the Fines of 2D <275 mm and 2D 200-90 mm. Within the categories (>20 mm), inert material makes up the largest part ranging between 5-23% of the total, with an average of 14% Also worth mentioning is the amount of glass in fraction 40-20 mm (4%). Together with the glass present in fraction 20-10 mm this confirms the previous assumption that glass is likely to break and pass to smaller grain-size fractions.

Looking at the PSD of the materials in Figure 13, a conclusion similar to the other outputs can be made: sieving with a mesh size of 40 mm may yield a material stream poor in glass but further enrichment does not seem realizable with the mesh sizes used in the analysis.

3.2.5 Overview of all output stream

Normally the 3D output streams of ballistic separators used to separate fresh waste contain stones, metals, glass, rubber and wood (H. Martens, 2016). In comparison, the results of the present paper show that the same applies for landfilled CDW and MSW with one exception: glass is only present in the finer fraction of the output stream <90 mm. Thus, considering the enrichment of highly calorific materials in the 2D streams, mostly 2D plastics, the ballistic separator seems to meet the expectations.

Nevertheless, a mass balance of the whole process must be considered to estimate a reliable potential for the whole landfill. This means that the composition of every output stream must be related to its share in the total flow when extrapolating the absolute mass of all materials stored in the landfill. Figure 15 presents the mass balance considering wet and dried material. However, the total water content must be higher than the indicated 25% because the moisture content of the output “3D >200 mm” was not analysed in this study and the water is evaporated during separation. Nevertheless, it points out the high share of particles in the output stream <90 mm, 58% of the input material, compared to 4% (dry) with RDF potential from which the fines separated by sieving must still be subtracted. Two main reasons are considered for the predominant share of fines: the longer the waste is stored, the more organic material can be degraded; thus, the amount of fines increases with time (Maul et al., 2016). Besides, the cover layer is a source of fines because usually soil is used as a daily cover (Kaartinen et al., 2013).

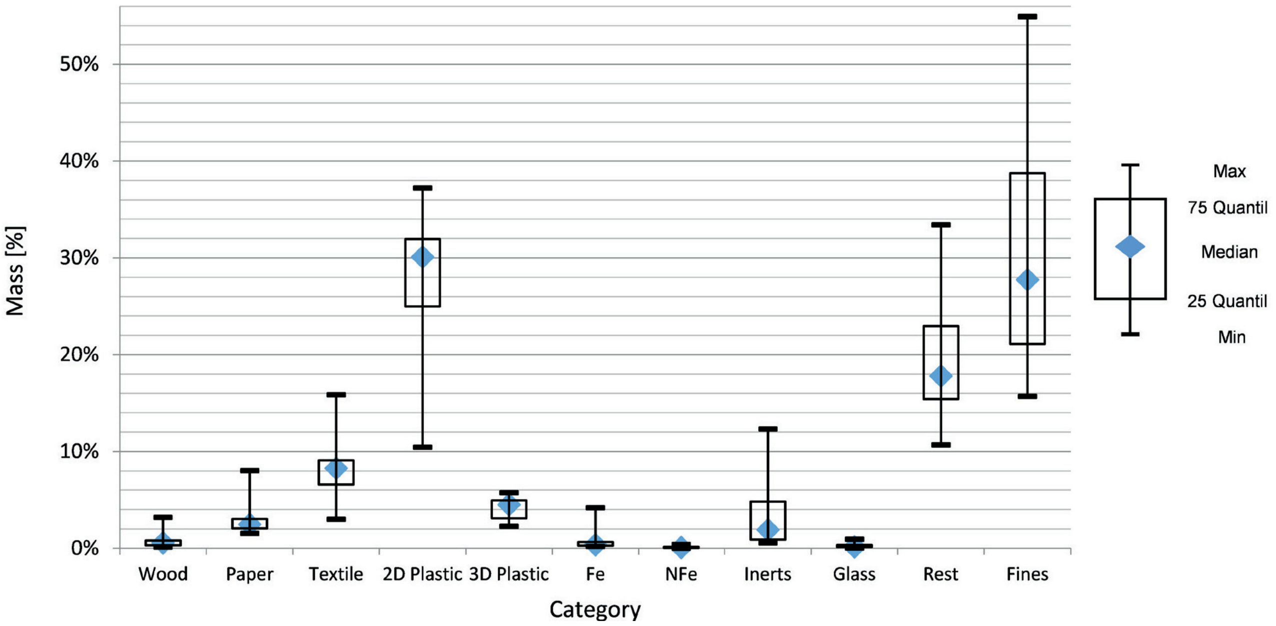


FIGURE 9: Output "2D <275 mm: fluctuations in the material composition, dm % (n=8).

FIGURE 10: Fines (<20 mm) from the output stream "2D <275 mm".

3.3 Calorific value and ash content

In order to assess the quality of the potential RDF produced by the ballistic separator, Table 2 shows the distribution of the calorific values, the ash content and the mass percentages by material categories in both 2D output stream, 2D <275 mm and 2D 200-90 mm.

As expected, 2D plastic, with a considerable share of the output streams, is the material with the highest calorific value, 35.1 and 40.9 MJ kg$^{-1,}$ followed by the 3D plastics with an average of 32.4 and 30.6 MJ kg 1. In the case of the Rest, the values are 18.5 and 23.3 MJ kg-1, which reinforce the previous assumption that this category can be regarded as a highly calorific fraction. Compared to the mean net calorific value of 21.9 MJ kg-1 (dry and ash free) for RDF (Phyllis database, 2018), the results of this study range within the same magnitude at 16.0 and 22.4 MJ kg^{-1}. Nevertheless, the influence of the fines is significant since they make up a third of the mass. This means that by separating fines from the stream before combustion, the amount of energy produced could be increased and the ash content could be reduced. In addition, only materials with ash contents <60% can burn autonomously (Seifert & Vehlow, 2017). In this regard, the 2D output streams have an ash content average of 50.5 and 40.4, thereby meet-

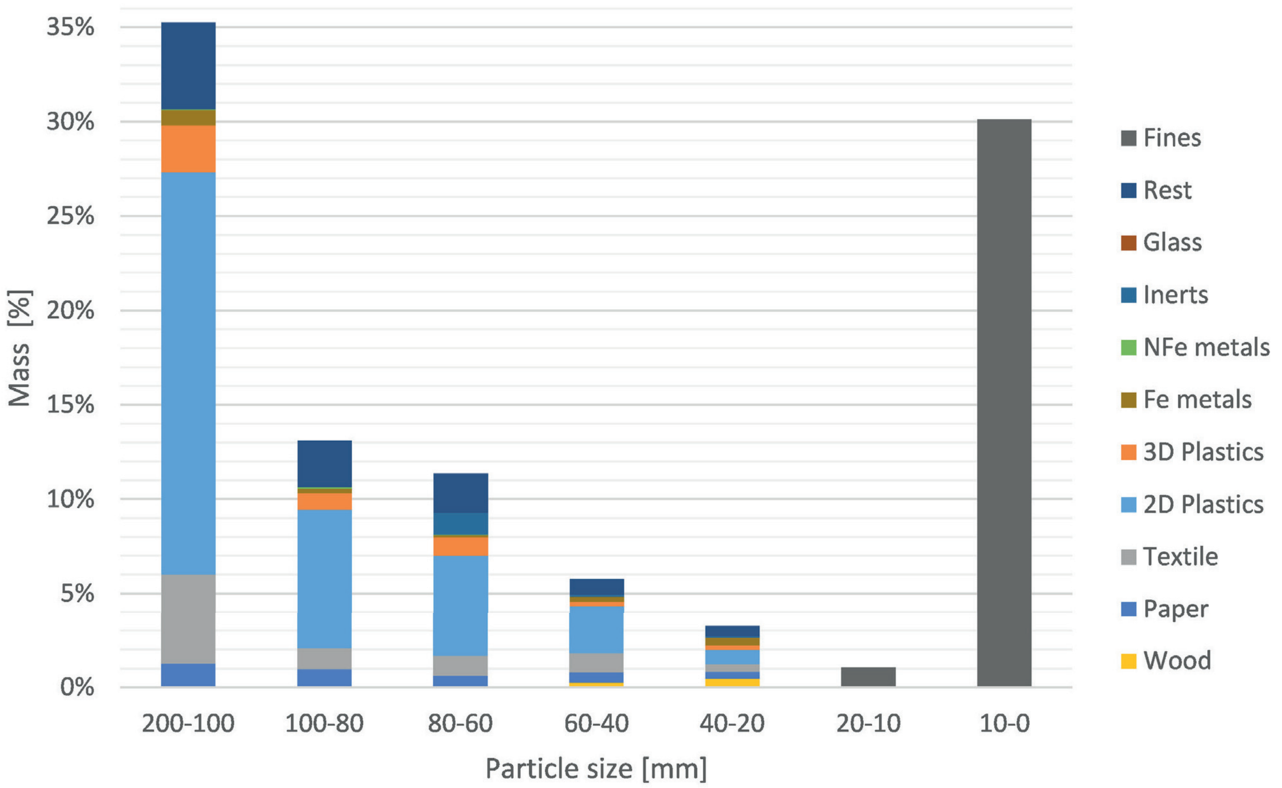


FIGURE 11: Material composition of the output stream "2D 200-90 mm" by particle size.

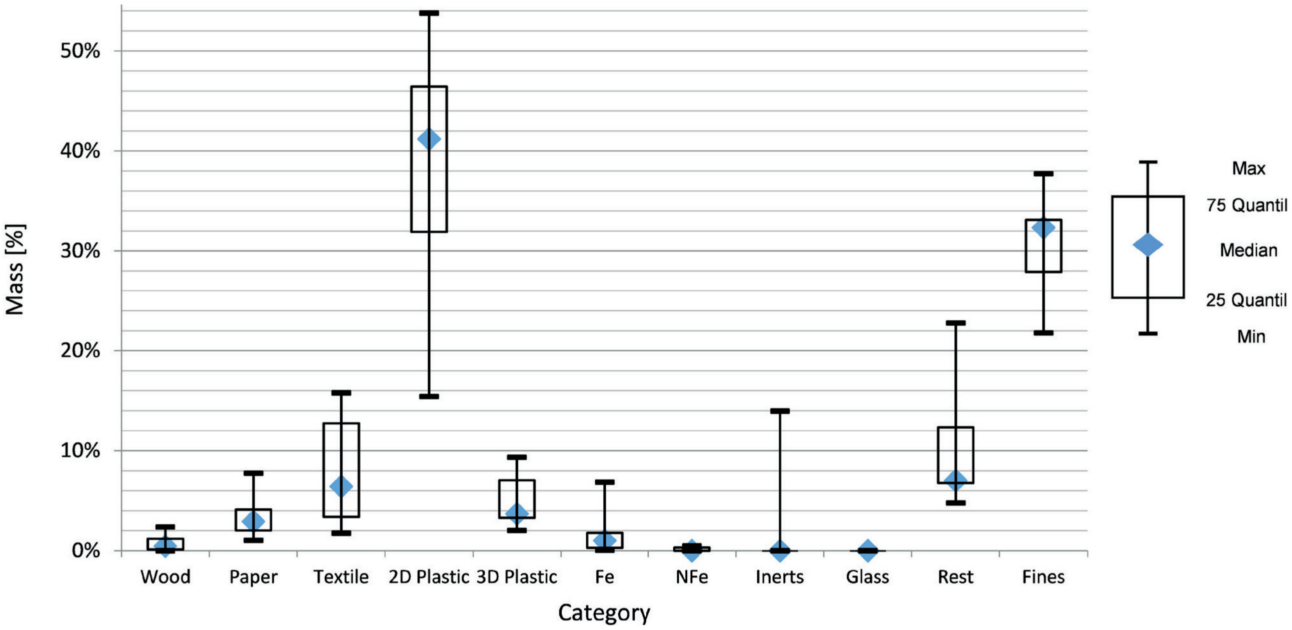


FIGURE 12: Output "2D 200-90 mm": fluctuations in the material composition, dm % (n=9).

ing this requirement. Moreover, low ash contents are also desirable to reduce the dust loading. It can be deduced from the low amount of materials that are not suitable for RDF (metals, inert and glass) and thus degrade the burning parameters, that the ballistic separator enriches RDF potential materials in the 2D stream as expected since the downgrading fines come from the surface of the RDF particles and were generated in the subsequent drying process.

3.4 Comparison with previous LFM investigations

The total range of moisture content was between 9 and 41%, comparable with data in the literature of 18 to 40% for 17 to 40 year old waste (Hernández Parrodi, 2018a),

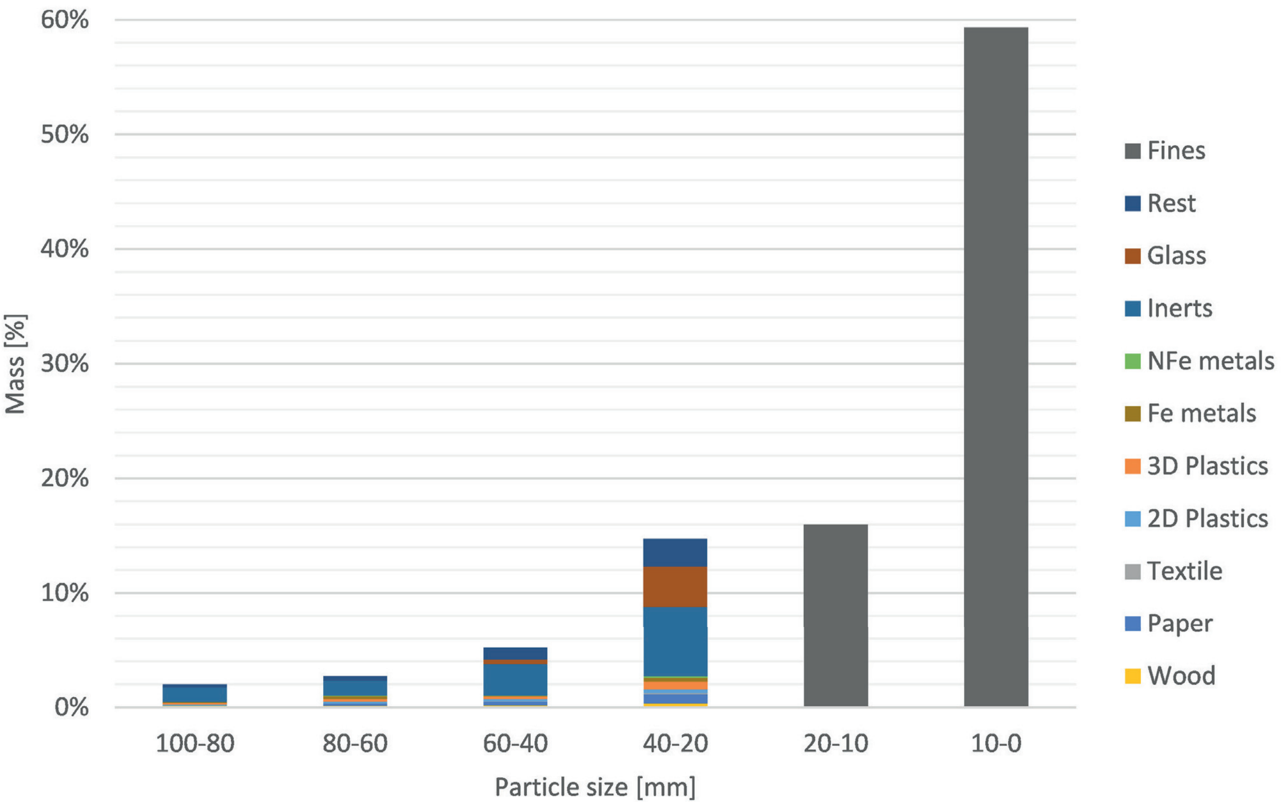


FIGURE 13: Material composition of the output stream "<90 mm" by particle size.

even if data from "3D >200 mm" is missing for a complete comparison. Apart from the age, other important parameters can influence the water content of the material, e.g., geographical location, landfill layering (water permeability), particle size and the type of waste landfilled.

The characteristics of the mined material depend strongly on the type of waste that was initially landfilled. This becomes evident when looking at the material composition indicated on a wet and mass basis from previous studies (Bhatnagar et al., 2017; Jani et al., 2016; Kaartinen et al., 2013; Quaghebeur et al., 2013; Van Vossen & Prent, 2011; Wolfsberger et al., 2015b). In Table 3, the inert fraction (17% in this study) makes up more of the total when CDW was deposited. Municipal landfills, on the other hand, are characterized by 10% of inorganic substance (concrete, stones, and glass), 20-30% highly calorific fraction and 27-54% soil-like materials. Thus, the share of plastics in MSW is considerably higher than the 3% found for mixed waste in this paper. The same holds for household waste materials, such as paper and textiles: the percentages counted are below the values reported in the literature (0.4% and 2-7%, respectively). With a share of approximately 46%, the fines (<20 mm) are in accordance with MSW but different particle sizes are used to define the fines or soil-like materials. The metal concentrations in most LFM projects range below 5%, nevertheless the 1% found seems low because more metals are expected from CDW, especially structural steel.

Similar to the difficulty encountered when comparing PSD, materials are classified into different categories by different researchers, especially overlapping categories (e.g., for plastics and metals) making comparison more challenging. Moreover, the efficiency of sorting, and therefore the results of the composition, depends on the applied technique: manual, mechanical or sensor-based sorting.

Findings on the GCV and ash content are compared to results presented by Quaghebeur et. al., 2013 for the REMO landfill site in Belgium. It stands out that the calorific value of the main combustible fraction (2D plastics, 35.1 and 40.9 MJ $kg^{-1)}$ is considerably higher than for plastics analysed by Quaghebeur et. al., 2013 (19.0-28.0 MJ kg^{-1}) with an ash content of 20-35% compared to 21,7% and 12,8% (12,8% and 11,8% for 3D plastics), depending on the 2D output stream in this study. Similar differences are noted for the ash content of paper and cardboard, which amounts to 25-61% at the REMO site but is only estimated to be 12% in this study. The CV of paper and cardboard is more conformable in both studies: 6.7-12.0 MJ kg^{-1} and 15 MJ kg^{-1}, respectively. The results for fines are in accordance with the compared data in which a CV of 1.3-4.8 MJ kg-1and ash contents of 64.4-87.5% are reported.

Summarizing the above comparison, it can be said that the mixture of CDW in the examined material with MSW influences the RDF potential negatively because MSW landfills are found to consist of more combustible materials. The high amount of fines described in most LFM projects is similar, whereas the CV and ash content are restricted in their resemblance. Standardized or widely agreed-on

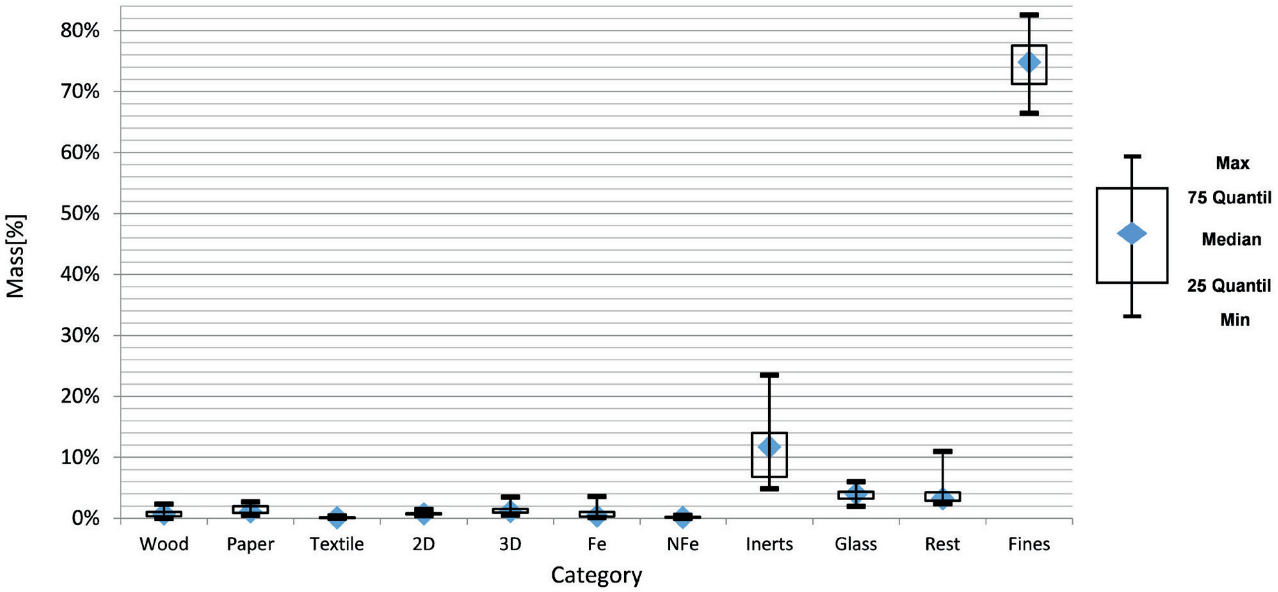


FIGURE 14: Output “<90 mm”: fluctuations in the material composition, dm % (n=12).

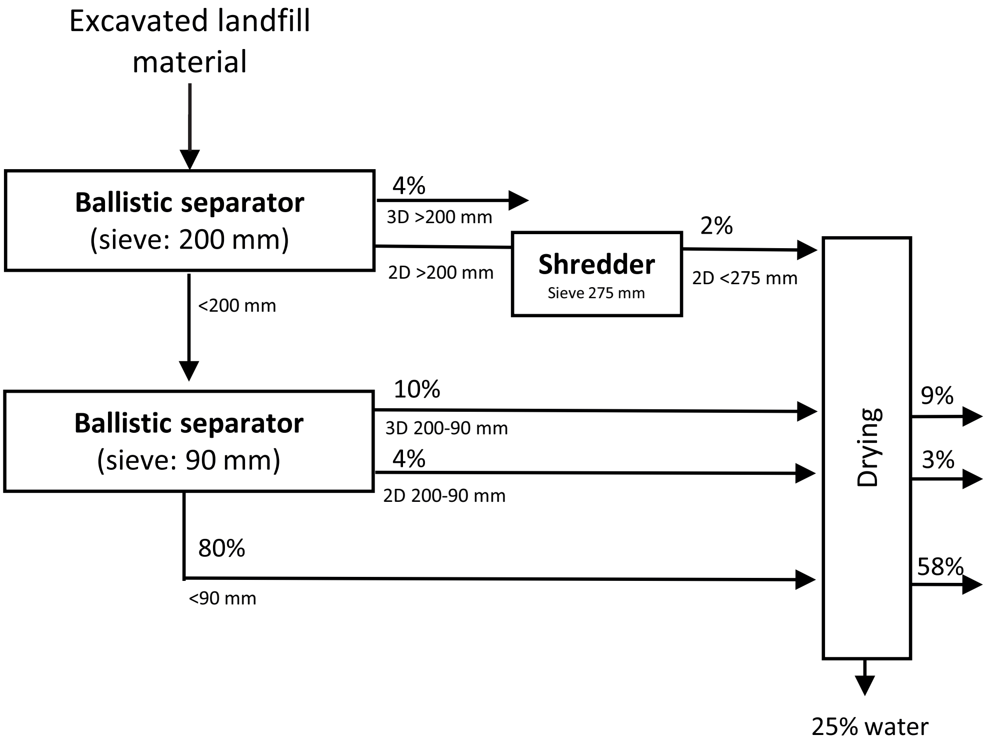


FIGURE 15: Mass balance of the ballistic separator with the two sieving steps of 200 mm and 90 mm (all indications refer to the input 100%).

material categories and particle size fractions to increase comparability are desirable.

3.5 Recovery options

Generally, two different recovery processes can be distinguished: WtM, which creates new materials according to the properties of the recovered materials and WtE, which can substitute for the use of fossil fuels. For fresh plastic waste both recovery options are practised. WtM (for plastics) is subdivided into primary recycling without modifications of the polymers, secondary recycling with downgrading and tertiary recycling with depolymerization reactions. Primary and secondary recycling requires high-quality incoming waste. Moreover, the possibility of meeting the limits on heavy metal content must be questioned, taking into account the diverse additives that were used in the past for plastic production. Tertiary recycling seems suitable for landfill-mined plastics but only a few industrial

TABLE 2: Average composition, GCV and ash content of the 2D <275 mm and 2D 200-90 mm output streams (n=8, n=9, respectively). Data from the REMO landfill (Quaghebeur et al., 2013) were used to compare the results.

Categories	2D < 275 mm			2D 200-90 mm			REMO, Belgium (2013)	
	Mass	GCV	Ash content	Mass	GCV	Ash content	GCV	Ash content
	[% of total]	[MJ/kg]	[%]	[% of total]	[MJ/kg]	[%]	[MJ/kg]	[%]
Wood	0,7	15,2	10,3	0,7	16,9	10,9	-	-
Paper	2,9	16,0	22,0	3,5	15,2	12	7.3 - 13.0	25.0 - 61.0
Textile	7,4	22,5	32,0	8,4	22,7	19,6	-	-
2D Plastics	24,1	35,1	21,7	37,5	40,9	13,5	19.0 - 28.0	20.0 - 35.0
3D Plastics	3,7	32,4	12,8	4,8	30,6	11,8		
Fe metals	0,9	-	100,0	1,7	-	100	-	-
NFe metals	0,1	-	100,0	0,2	-	-	-	-
Inert	5,7	0,1	98,4	1,5	-	99,6	-	-
Glass	0,4	-	100,0	0,0	-	-	-	-
Rest	18,0	18,5	34,7	10,5	23,3	16,8	-	-
Fines	36,1	2,0	79,0	31,2	1,9	88	2.1 - 5.7	64.4 - 87.5
Total	100,0	16,0	50,5	100,00	22,4	40,4	-	-

plants applying this process exist in Europe (Quaghebeur et al., 2013). Likewise, the heterogeneity and high level of contamination of paper, textiles and wood would require extensive and expensive treatment for WtM valorisation of those materials. As mentioned above, the Rest of the “2D 200-90 and 2D <275 mm” also appears suitable for WtE. Hence, for most excavated materials WtE valorisation as “Solid recovered fuels (SRF) is the most realistic marketable material” (Bhatnagar et al., 2017). RDF differs from SRF in that the latter guarantees a certain quality of the fuel, since SRF must be produced from non-hazardous waste and fulfil certain fuel qualities (Rotter et al., 2011). Therefore, more parameters, apart from the characteristics presented in this study, are needed to evaluate the efficiency and quality of the RDF generated from landfilled materials and the emissions of the combustion process. Those parameters are the amount of organic carbon, total carbon, hydrogen, nitrogen, sulfur, chlorine, fluorine, bromine and heavy metals (Quaghebeur et al., 2013). It is obligatory to indicate the concentration of chlorine according to the specification DIN EN 15359 due to its corrosive impact and the property of mobilizing some of the metals into the flue gas (Kaartinen et al., 2013). Heavy metals are of special concern for SRF made from pretreated waste (Wolfsberger et al., 2015a). Therefore, information should be gathered about the history and origin of the landfilled waste. The requirements that the above parameters must meet depend on the combustion system used and on applicable laws and authorization procedures (Kuchta et al., 2017).

If metals are not separated during the SRF/RDF production process and are directly valorised as WtM, they can be recovered from the ash after incineration (Seifert & Vehlow, 2017) .As glass is an inert material, WtM is considered for its valorisation providing an efficient separation (Quaghebeur et al., 2013).

Of major importance is the recoverability of the fine fractions, as they make up around half of the total material excavated and have been found to be challenging in previous investigations (Hernández Parrodi et al., 2018; Jones et al., 2013). A WtE application of the fine fractions, as described by Quaghebeur et. al., 2013, is not considered to be applicable for the present material because of the age of the waste, the resulting high degree of degradation, the low CV and the high ash content. Thus, WtM options are to be considered.

One possibility is the use of the fine fractions as a cover layer in operating landfills. At the Kudjape landfill, Estonia, the fine fraction was used as a methane degradation layer. This valorisation requires a low degree of contamination (Bhatnagar et al., 2017). The use of fines and conditioned inert materials as filler and construction material generally can be considered if they comply with the limit values for such activities (Quaghebeur et al., 2013).

Heavy metals are especially expected to be found in old landfills and can contribute to decrease the costs of ELFM if recovered (Garcia Lopez et al., 2018). From these findings, the recovery of the major and trace metals from the fine fractions could be an option to meet the globally increasing demand. Conducting leaching tests and XRF analysis can give a more precise composition determination and allow an estimation of the marketable potential. Apart from the potential economic benefit of heavy metals recovery from the fine fractions, another positive effect can be the resulting reduction of their uncontrolled leaching out of the landfill (Hernández Parrodi et al., 2018; Bhatnagar et al., 2017; Quaghebeur et al., 2013; Kaartinen et al., 2013).

A third option would be to re-landfill the fine fractions, but this procedure bears costs instead of revenues and

TABLE 3: Comparison of the material composition of this study with previous LFM investigations, adapted from Hernández Parrodi, 2018a.

Type of information	This study, 2018 (MSG, Belgium)	Various countries (Van Vossen and Prent, 2011)	Högbytorp, Sweden (Jani et al., 2016)	Kuopio, Finland (Kaartinen et al., 2013)	Kudjape, Estonia (Bhatnagar et al., 2017)	Lower Austria, Austria (Wolfsberger et al., 2015)	Houthalen, Belgium (Quaghebeur et al., 2013)
Type of waste	MSW + C&D	Various	MSW + C&D	MSW	MSW	MSW	MSW
Age of waste [y]	40 - 50	Various	5	5 - 10	10	13 -20	14 - 29
Average moisture content	25%	-	-	-	-	29 - 55%	48 - 66%
Fines/ Soil-like material	46%	55%	27%	50-54%	29%	47%	44% (12)
Stones	-	3%	28%	-	18%	-	-
Inert/minerals	17%	6%	-	-	-	6%	10% (6)
C&D	-	9%	-	-	-	-	-
Limestone	-	-	5%	-	-	-	-
Asphalt	-	-	3%	-	-	-	-
Glass/ceramics	2%	1%	6%	-	5%	1%	1.3% (0.8)
Plastics (3D/2D)	3%	5%	-	23%	22%	18%	17% (10)
Soft plastics	-	-	1%	-	-	-	-
2D plastics	2%	-	-	-	-	-	-
3D plastics	1%	-	-	-	-	-	-
Other plastic/ Composites	-	-	7%	-	-	4%	-
Organic/kitchen waste	-	5%	-	-	-	-	-
Paper/cardboard/ PPC	1%	5%	-	4 - 8%	5%	3%	7.5% (6)
Paper	<1%	-	4%	-	-	-	-
Wood	1%	4%	15%	6 - 7%	5%	-	6.7% (5)
Textile	<1%	2%	3%	7%	-	6%	6.8% (6)
Leather	-	2%	-	-	-	-	-
Rubber	-	-	0%	-	-	-	-
Wood/leather/rubber	-	-	-	-	-	9%	-
Total metals	1%	2%	-	3 - 4%	3%	5%	2.8% (1)
Fe metals	1%	-	0%	-	-	-	-
NFe metals	<1%	-	0%	-	-	-	-
Other/ Rest	3%	3%	-	2%	13%	1%	-
Non-MSW	-	0%	-	-	-	-	-

is not in line with the introduced goals of ELFM projects (Kaartinen et al., 2013).

Independently of the recovery option chosen for the fine fractions, their separation from other excavated materials by sieving can be essential for further processing, since it raises the purity and CV of the RDF stream and improves the possible efficiency of sensor-based sorting techniques (Hernández Parrodi et al., 2018; Maul et al., 2016). Moreover, the bulk density of the material is a very relevant parameter for the design of the mechanical treatment. Although no quantitative statement was done in this analysis, it can be said that landfilled material presents higher bulk densities than fresh MSW, since the landfill-mined material showed more fine material than those typical of MSW.

4. CONCLUSIONS

This study found that the 3D-output streams (>200 mm and 200-90 mm) of the ballistic separator consisted mainly of coarse CDW, whereas more heterogeneous MSW was yielded in the 2D-output streams (>200 mm and 200-90 mm). By comparing 57% of the combustible materials (plastics, paper, textiles, leather and wood) in the output "2D <275 mm" and 65% in "2D 200-90 mm" to 75% of inert material in "3D 200-90 mm", the efficiency of the separating process was suitable for the landfilled material. The 2D-output streams were characterized by a higher moisture content (average, 30%) than the 3D streams (12%), which caused elevated amounts of fines (<20 mm) to adhere to larger particles.

The laboratory analysis showed an average CV of 22

MJ kg^{-1} and an ash content of 40% for the “2D 200-90 mm”. To fully determine the quality of the produced RDF, further tests that characterize the generated flue gas and remaining ash should be conducted.

A considerable share of the total excavated waste was made up of the output stream <90 mm, which was the greatest output stream of the ballistic separator with a share of 80% (wm). Its amount is expected to increase if the material is dried beforehand. As a further processing step, separating the fines by sieving is advisable to remove inert materials and enrich the WtE-stream with high CV materials, since fines contain a significant amount of inert materials, which are not suitable for RDF production. WtM valorisation of the recovered materials, such as inert materials as construction sand, soil-like materials as cover material for operational landfills or metals for recycling, could be considered for the fine fractions. If the separation of metals, glass and stones is possible, the amount of material that has to be re-landfilled would be decreased significantly.

The results of this study cannot be directly transferred to other landfills because compositions depend on different factors such as the origin of the waste, time of storage and physical conditions of the site. In this study, the ballistic separator shows an enhanced mechanical processing due to the share of CDW, which mostly consists of heavy 3D-materials. Further investigation is required in order to state that different types of waste (industrial waste, MSW and CDW, independently) have the same rate of enrichment of high calorific materials as in this study.

Although this study assesses the technical aspects by characterizing the different output streams generated by the ballistic separator, cost efficiency also needs to be taken into account when considering the feasibility of a full-scale ELFM project. Additionally, a remaining challenge is the assessment of costs and revenues of a recovery process by estimating the total amount of deposited waste and relating it to the market prices of the recoverable materials.

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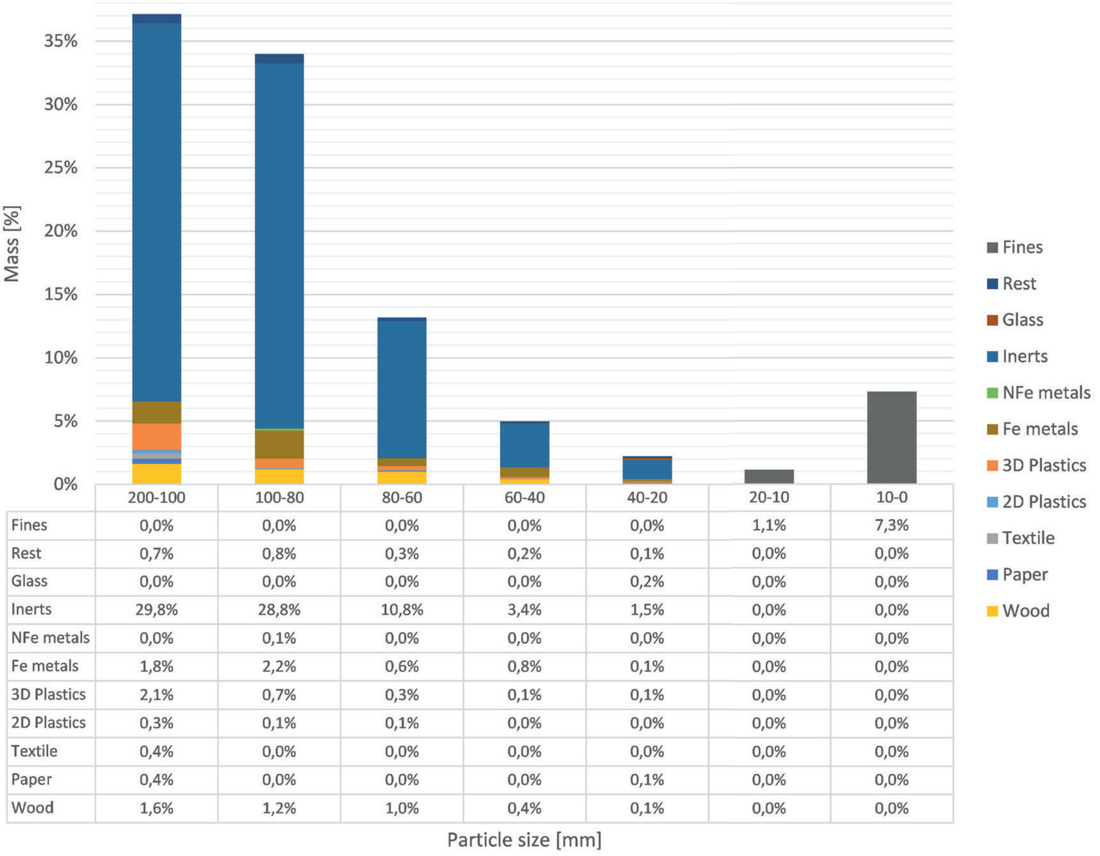
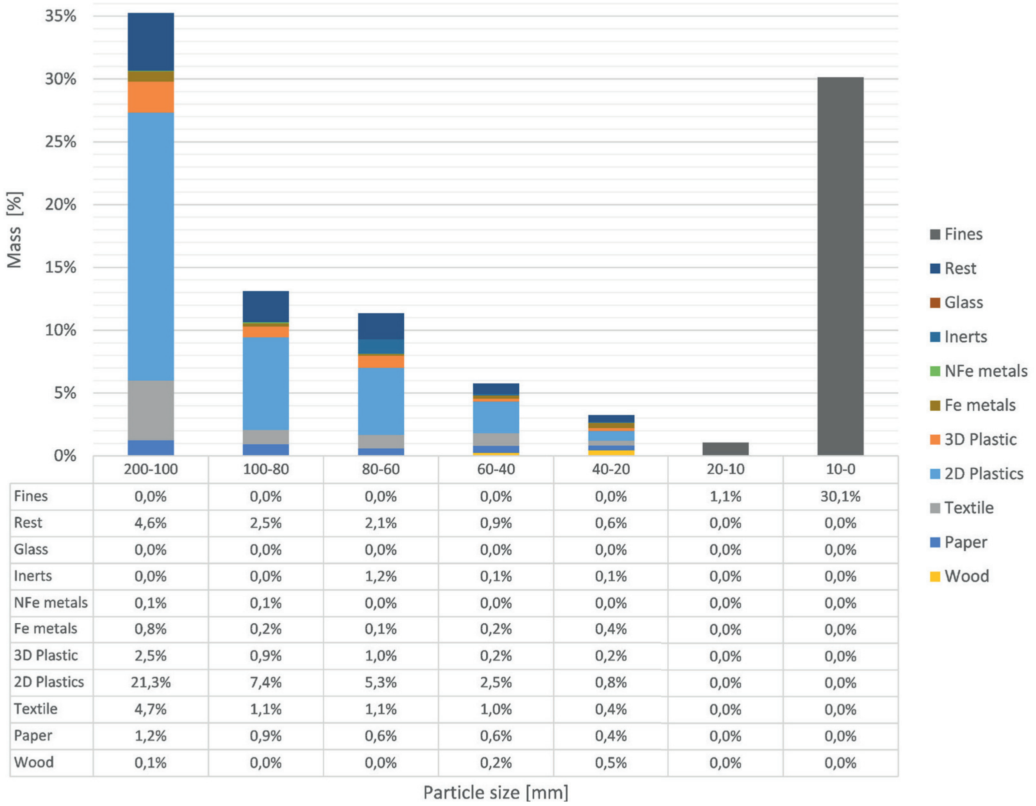
APPENDIX A



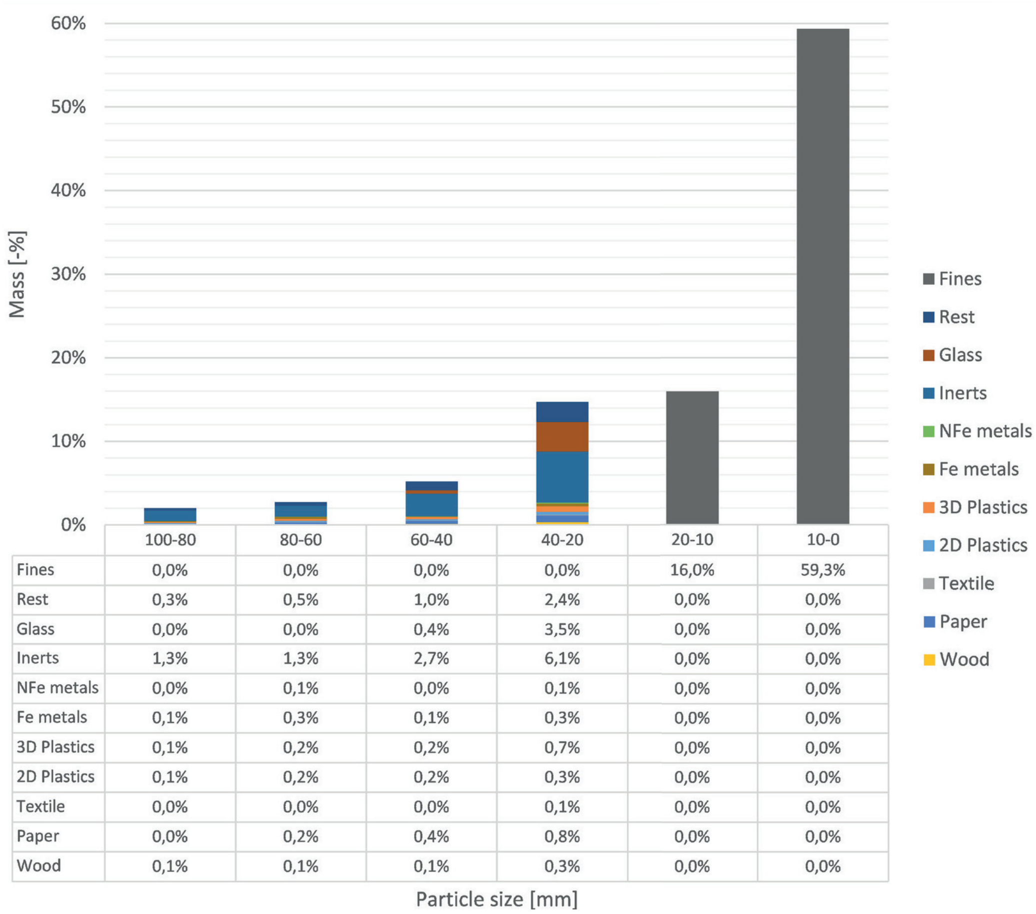
	200-100	100-80	80-60	60-40	40-20	20-10	10-0
Fines	0,0%	0,0%	0,0%	0,0%	0,0%	1,1%	7,3%
Rest	0,7%	0,8%	0,3%	0,2%	0,1%	0,0%	0,0%
Glass	0,0%	0,0%	0,0%	0,0%	0,2%	0,0%	0,0%
Inerts	29,8%	28,8%	10,8%	3,4%	1,5%	0,0%	0,0%
NFe metals	0,0%	0,1%	0,0%	0,0%	0,0%	0,0%	0,0%
Fe metals	1,8%	2,2%	0,6%	0,8%	0,1%	0,0%	0,0%
3D Plastics	2,1%	0,7%	0,3%	0,1%	0,1%	0,0%	0,0%
2D Plastics	0,3%	0,1%	0,1%	0,0%	0,0%	0,0%	0,0%
Textile	0,4%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
Paper	0,4%	0,0%	0,0%	0,0%	0,1%	0,0%	0,0%
Wood	1,6%	1,2%	1,0%	0,4%	0,1%	0,0%	0,0%

FIGURE A1: Total mass composition, dm %, by particle size of the output "3D 200-90 mm".



	200-100	100-80	80-60	60-40	40-20	20-10	10-0
Fines	0,0%	0,0%	0,0%	0,0%	0,0%	1,1%	30,1%
Rest	4,6%	2,5%	2,1%	0,9%	0,6%	0,0%	0,0%
Glass	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
Inerts	0,0%	0,0%	1,2%	0,1%	0,1%	0,0%	0,0%
NFe metals	0,1%	0,1%	0,0%	0,0%	0,0%	0,0%	0,0%
Fe metals	0,8%	0,2%	0,1%	0,2%	0,4%	0,0%	0,0%
3D Plastic	2,5%	0,9%	1,0%	0,2%	0,2%	0,0%	0,0%
2D Plastics	21,3%	7,4%	5,3%	2,5%	0,8%	0,0%	0,0%
Textile	4,7%	1,1%	1,1%	1,0%	0,4%	0,0%	0,0%
Paper	1,2%	0,9%	0,6%	0,6%	0,4%	0,0%	0,0%
Wood	0,1%	0,0%	0,0%	0,2%	0,5%	0,0%	0,0%

FIGURE A2: Total mass composition, dm %, by particle size of the output “2D 200-90 mr



	100-80	80-60	60-40	40-20	20-10	10-0
Fines	0,0%	0,0%	0,0%	0,0%	16,0%	59,3%
Rest	0,3%	0,5%	1,0%	2,4%	0,0%	0,0%
Glass	0,0%	0,0%	0,4%	3,5%	0,0%	0,0%
Inerts	1,3%	1,3%	2,7%	6,1%	0,0%	0,0%
NFe metals	0,0%	0,1%	0,0%	0,1%	0,0%	0,0%
Fe metals	0,1%	0,3%	0,1%	0,3%	0,0%	0,0%
3D Plastics	0,1%	0,2%	0,2%	0,7%	0,0%	0,0%
2D Plastics	0,1%	0,2%	0,2%	0,3%	0,0%	0,0%
Textile	0,0%	0,0%	0,0%	0,1%	0,0%	0,0%
Paper	0,0%	0,2%	0,4%	0,8%	0,0%	0,0%
Wood	0,1%	0,1%	0,1%	0,3%	0,0%	0,0%

FIGURE A3: Total mass composition, dm %, by particle size of the output “<90 mm”.

APPENDIX B

TABLE B1: Technical specifications of the ballistic separator.

Manufacturer	**STADLER®**
Modell	STT 6000
Dimensions (L x W x H) (mm)	6030x2970x6040
Weight (kg)	25000
Engine output (kW)	30
Adjustable Angle	15°; 17.5°; 20°
Surface (m^2)	14.3
Maximum output (m^3/h)	200
N° of paddles	5
N° of fans	No fans available

TABLE B2: Technical specifications of the sieves.

	Drum sieve	**Box sieve**
Manufacturer	Self-made by the Department of Processing and Recycling (RWTH Aachen University)	Siebtechnik
Type of movement	Rotating	Circular Vibratory Screen
Input power (kW)	2.2	0.75
Diameter of drum screen (mm)	1500	-
Installation	Polygonal screen with 8 screen linings	-
Dimensions of screen linings (mm)	950x560	500x500
Revolution	Adjustable	1400 RPM
Mesh sizes (mm)	10; **20; 40; 60; 80; 100**; 120; 140; 160; 200; 240; 300	1; 2; 4; 6.3; **10; 20**; 31.5; **40**; 50; **60**; **80**; 100
**The mesh sizes used during this study are marked in bold.*		

TABLE B3: Technical specifications of the sieves.

Type of cutting mill	**Large cutting mill**	**Small cutting mill**	**Disc mill**
Manufacturer	Reto	Dreher	Retsch
Input power (kW)	37	2.2	1.75
Rotor peripheral speed (m/s)	9	10	10
Rotor cutting diameter (mm)	350	160	
Rotor length (mm)	450	200	
Mesh sizes (mm)	4; **5**; 6; 8; **10**; 12; 15; 20; 30; 40; 50; 60; 70; 80	**1**; **2**; 3; 4; 5; 6; 8	**0.5**; 0.75; **1**; 1.5; **2**; 4; 6; 8; 10
**The mesh sizes used during this study are marked in bold.*			

TABLE B4: Technical specifications of the hammer mills.

	Large hammer mill	**Small large mill**
Manufacturer	Hazemag	Condux
Type of crusher	High speed	High speed
Main types of loads	-	Impact, Shearing
Weight (kg)	-	30
Input power (kW)	18	3
Revolution	adjustable up to approx.19 m/s	2850 RPM
Mesh sizes (mm)		
Feed grain size (mm, max.)	*approx. 360 x 280*	*100 x 60*
Rotor width (mm)	-	*150*

6 MONT-SAINT-GUIBERT CASE STUDY: MAIN CHARACTERISTICS OF THE FINE FRACTIONS

Scientific article no. 5: “Case Study on Enhanced Landfill Mining at Mont-Saint-Guibert Landfill in Belgium: Characterization and Potential of Fine Fractions”

Hernández Parrodi, J.C., Garcia Lopez, C., Küppers, B., Raulf, K., Vollprecht, D., Pretz, T., Pomberger, R., 2019. Case Study on Enhanced Landfill Mining at Mont-Saint-Guibert Landfill in Belgium: Characterization and Potential of Fine Fractions. Detritus 8 (1), 47–61. 10.31025/2611-4135/2019.13877.

Annotation on my personal contribution to this scientific article:

The samples of the fine fractions were taken with assistance of Cristina García López and Bastian Küppers at the landfill site. In consultation with Karoline Raulf, Daniel Vollprecht, Roland Pomberger and Thomas Pretz I conceived the plan for the characterization of the fine fractions and the identification of the most adequate valorization routes. The characterization activities were carried out by me and support was provided by Cristina García López, Karoline Raulf and Thomas Pretz. Most of the paper was written by me and the analysis and interpretation of the results was done in consultation with all authors. All authors reviewed the article and I performed the revision.

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CASE STUDY ON ENHANCED LANDFILL MINING AT MONT-SAINT-GUIBERT LANDFILL IN BELGIUM: CHARACTERIZATION AND POTENTIAL OF FINE FRACTIONS

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ABSTRACT
Within the framework of the "EU Training Network for Resource Recovery through Enhanced Landfill Mining – NEW-MINE", around 374 Mg of waste were excavated from a landfill site in Mont-Saint-Guibert, Belgium. Parameters such as bulk density, water content, particle size distribution and material composition of the fine fractions (material <90 mm) were determined and analyzed. The present investigation has the main objective to document and disseminate the findings on the material characterization of the fine fractions obtained in this case study, since such information is of critical relevance for the design of an effective and efficient mechanical processing in (enhanced) landfill mining projects. Additionally, the potential of the fine fractions for material and energy recovery is discussed. The fine fractions in question were obtained through the implementation of a ballistic separation process with simultaneous screening directly after excavation, from which about 77 wt.% of the total amount of processed material in raw state corresponded to the fine fractions. These fractions presented an overall bulk density range of 720-1000 kg/m^3 in raw state and a total water content range of 25-30 wt.%. In dry state, the material showed a more uniform particle size distribution than in raw state, and results confirm that water content has a large impact on the particle size distribution of the fine fractions, as well as on the content of impurities in the material fractions "Combustibles", "Inert", "Total metals" and "Others" and on the presence of agglomerates. Results on the material composition in dry state reveal that amounts of 2.1-19.7 wt.% "Combustibles", 31.1-35.4 wt.% "Inert" and 0.6-1.8 wt.% "Total metals" could be recovered from the fine fractions 90-10 mm, while 37.8-55.6 wt.% "Fine fractions <10 mm" could be processed further in order to increase the recovery amounts of the previous material fractions and produce a substitute material for soil in construction applications.

1. INTRODUCTION

In general terms, (enhanced) landfill mining ((E)LFM) aims for the mitigation of pollution originating from landfill sites, reduction of aftercare and closure costs, land reclamation in urban areas, material recovery and, among many others, regaining landfill capacity (Hernández Parrodi et al., 2019; Hull et al., 2005; Jones et al., 2013; Jones et al., 2010; Jones and Tielemans, 2010; Krook et al., 2012). Particularly, the recovery of materials from the excavated material for recycling and production of alternative fuels has been included into the scope of many recent investigations in an attempt to raise the overall economic feasibility of (E) LFM projects (Hernández Parrodi et al., 2018a, 2018b). Nevertheless, mainly the coarse fractions (material with a particle size ≥10 mm to ≥60 mm, depending on the investigation) have been used for waste-to-material (WtM) and waste-to-energy (WtE) purposes in those investigations.

Concurrently, it has been identified in previous research that fine fractions (material with a particle size <60 mm to <10 mm, depending on the investigation), which represent about 40-80 wt.% of the total amount of excavated material, can be a relevant source for material and energy recovery (Hernández Parrodi et al., 2018a, 2018b). These fractions have been re-directed to the landfill, to a large extent, with poor or without any treatment at all (Bhatnagar et al., 2017; Münnich et al., 2013) and, therefore, the exploitation of their potential is of utmost relevance to increase the overall

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material and energy recovery in (E)LFM projects.

In order to assess the potential for material and energy recovery from the fine fractions of a particular landfill site, it is necessary to determine their material composition and main characteristics, such as bulk density, water content and particle size distribution (PSD). The present study has the main aim to document and disseminate the findings of the material characterization obtained through this investigation, as well as to discuss the potential of the examined fine fractions for WtM and WtE.

2. MATERIALS AND METHODS

2.1 Site description

The investigated landfill site in this case study is the "Centre d´enfouissement Technique de Mont-Saint-Guibert (CETeM)" located in the municipality of Mont-Saint-Guibert (MSG), Belgium (Figure 1a). Founded on a former sand quarry, which was exploited from 1937 to 1985, this landfill has served as one of the main disposal sites of municipal solid waste (MSW), non-hazardous industrial waste (IW) and construction & demolition waste (C&D) to the Belgian province of Walloon Brabant from 1958 (Bureau d´études greisch, 2002) to 2014. Nowadays, this site is going through its closure process, which is expected to conclude by the end of 2020.

MSG landfill has a total area of around 44.3 ha (D´Or, 2013), which is delimited in yellow in Figure 1b. The total area is divided into two main parts, namely the modern part and the old part of the site. The modern part has an area of about 26.5 ha (IGRETEC, 1994), which is delimited in blue in Figure 1b, while an estimated area of 14 ha corresponds to the old part, which is delimited in red in Figure 1b.

The present investigation was carried out at the old part of the landfill, which has an estimated depth between 30 m and 60 m and where at least 5.7 million m^3 of waste were disposed of between 1958 and 1985 (Gaël et al., 2017; IGRETEC, 1994). The old part of the landfill had a biogas collection system of vertical wells during the 1980s, which was removed after the stabilization of the waste, and has a functioning leachate collection system that consists of a lateral drain still in place.

Multi-sensor geophysical data from the subsurface of the old landfill´s body were gathered from three different areas during July-August 2017, from which one of them was selected for further geophysical exploration. Some decisive criteria for the selection of the exploration area were lateral and vertical extents, as well as the largest possible

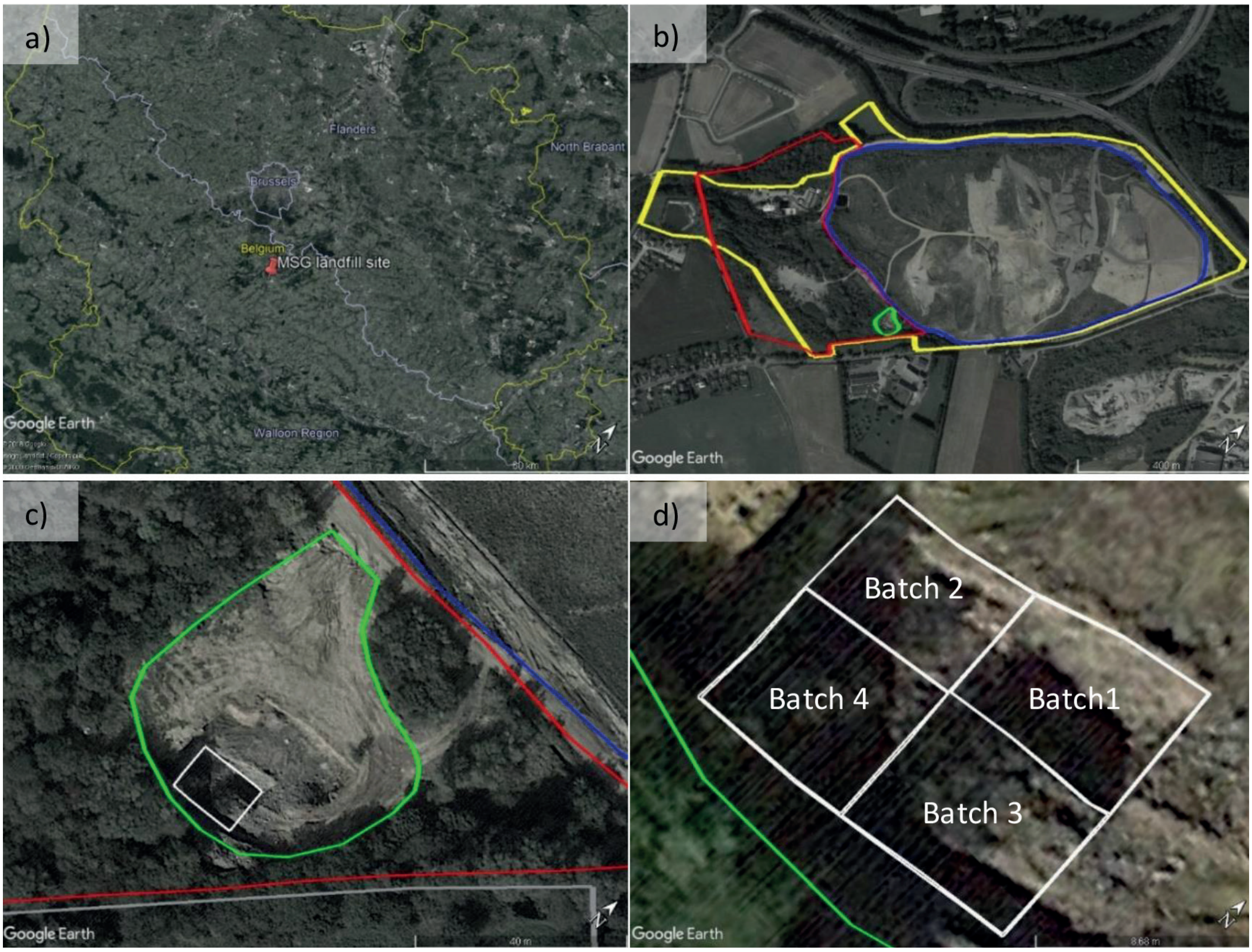

FIGURE 1: a) Location of landfill site in Belgium, b) MSG landfill site, c) exploration area and excavation zone and d) excavation zone with batches.

range of apparent surface electrical conductivity. The selected geophysical exploration area was around 2150 m^2, which is delimited in green in Figure 1b,c. Based on the results of the geophysical measurements, an excavation zone was selected within the selected exploration area due to its potential to validate measured geophysical properties of various unknown materials, since it was assumed a priori that a large variation range in electrical conductivity would coincide with a large variation in type of materials. The selected excavation zone had an area of about 130 m^2 and is delimited in white in Figure 1c. This zone is shown in greater detail in Figure 1d as well.

The concessioner for the operation of the landfill site is the company Renewi Belgium SA/NV, which has operated the site for over 25 years and provided most of the necessary equipment and manpower to realize this study.

2.2 Excavation works and material pre-processing

The material excavation and mechanical pre-processing were carried out during the last week of August and first week of September, 2017. The total excavated volume was divided into four sub-volumes, which are henceforth referred to as batches in this study (Figure 1d). The excavated volume was about 10 m long, 10 m wide and 4 m deep, while batches were around 5 m long and 5 m wide and had varying depths. The batches were classified in-situ according to their composition, since a clear waste stratification was identified visually within the excavated volume. As shown in Figure 2b, the first 2 m of the excavated volume consisted of a layer of mainly C&D, whereas below this layer the material corresponded to a layer of about 2 m of mostly MSW with daily cover layers of clay in between. Batch 1 and batch 2 were both excavated completely and, therefore, they were mainly composed of a mixture of MSW and C&D. For batch 3 and batch 4 the layers of C&D (upper layer) and MSW (bottom layer) were excavated individually in such a way that they predominantly consisted of C&D and MSW, respectively. Batches 1 to 4 were handled separately with the main purpose of studying their characteristics and mechanical processability as a mixture of C&D and MSW (batch 1 and batch 2) and as mostly C&D (batch 3) and MSW (batch 4), which allowed to obtain a more detailed insight into the performance of the mechanical processing with significant variations in the input material.

For the extraction of the waste material from the landfill, Hitachi 250LC and Liebherr 934 excavators with toothed digging type buckets of 2.5 m^3 were employed, while for the manipulation of the excavated material a Caterpillar 972K wheel loader equipped with a 3.5 m^3 bucket was utilized

FIGURE 2: a) Material excavation, b) excavation volume, c) ballistic separator and d) fine fractions.

(Figure 2a,c). During the excavation works the cover layer was removed first, which was mainly composed of clay and had an estimated average thickness of about 4 m (Figure 2b), in order to keep it separated from the landfilled waste. The cover layer material was not further processed. Subsequently, the excavated material was transported with Caterpillar 730C articulated trucks of 13.9 m^3 (each) from the excavation zone to the mechanical pre-processing area (Figure 2a,c). The weight of the excavated material was determined with a weighing bridge of 50 Mg capacity and a resolution of 50 kg.

The fine fractions were obtained through the implementation of a two-step ballistic separation process (Figure 2d) with simultaneous screening (screening paddles). The ballistic separator (Stadler model STT 6000) sorted the input material into three-dimensional (3D), two-dimensional (2D) and under-screen fractions according to density, shape and particle size differences. In the ballistic separation process the screening paddles were firstly set to sieve the input material at 200 mm and subsequently at 90 mm. In this case study the fine fractions were defined as the excavated landfill material with a particle size <90 mm obtained from the second processing step of the ballistic separator. Figure 3 provides a schematic overview of the ballistic separation process, as well as of the outputs from which samples were taken. Additional details about the ballistic separator and the mechanical pre-processing and processing of the coarse fractions (≥90 mm) can be found in García López et al., 2019.

After being pre-processed with the ballistic separator, the fine fractions were loaded into containers of 25 m^3 with a Manitou MRT 2150 telescopic handler equipped with a 2.5 m^3 bucket to be stored until further processing.

2.3 Material samples and laboratory analysis

Due to the large amount of material excavated and pre-processed, representative single samples of the output fractions of the ballistic separator were taken for further analysis (Figure 4a). In this way, the quantity of material to be characterized and the amount of laboratory analysis can be reduced without compromising the reliability of the results. For this, the German guideline for procedures for physical, chemical and biological testing in connection with the recovery/disposal of waste (LAGA PN 98) was followed, which specifies the amount and size of the samples to be taken, according to the type, amount and particle size of the material to be sampled.

The sampling of the obtained fine fractions was done directly at the output chute of the ballistic separator. Two single samples of 10 l (each) were taken every 7.5 minutes in order to accumulate an amount of sixteen single samples per batch of processed material in 1 h. Eight composite samples (Figure 4c) of 20 l (each) were prepared on-site from every set of sixteen single samples, using the quartering method, as shown in Figure 4b.

The composite samples were used to determine the material composition and physical properties of the fine fractions at the raw materials laboratory and technical facility of the Department of Processing and Recycling (IAR) of the RWTH Aachen University. The material characterization was done in dry and raw states in order to allow direct comparison of the results. A circular vibratory box

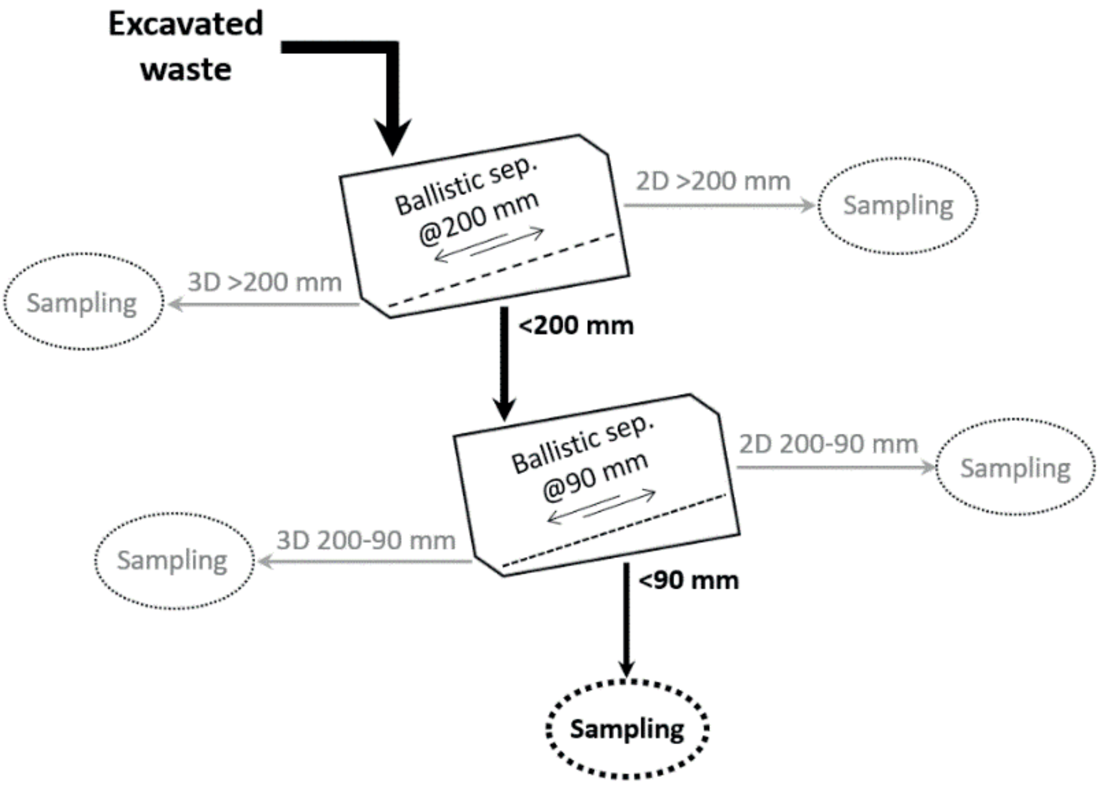

FIGURE 3: Pre-processing of excavated waste with ballistic separator.

FIGURE 4: a) Single samples, b) quartering method and c) composite samples.

sieve (Siebtechnik, 500 mm x 500 mm) with circular reticle sieves of 63 mm, 31.5 mm and 10 mm and a circular vibratory sieve tower (Siebtechnik, Ø 400 mm) with squared reticle sieves of 6.3 mm, 3.15 mm, 1.0 mm, 0.63 mm, 0.315 mm and 0.16 mm were used to determine the PSD, which was performed according to the norm DIN EN 15415-1:2011. Water and dry mass contents were determined according to the norm DIN EN 14346 (modified: drying at 75°C ± 5°C to prevent loss of volatile matter and melting of certain plastics). The drying of the samples was done in a Heraeus industrial drying oven. For the determination of the bulk density, the norm DIN SPEC CEN/TS 15401:2010 was followed. An industrial platform scale (Kern DS 150K1, resolution of 1.0 g) and a precision balance (Kern KB 2400-2N, resolution of 0.01 g) were used to determine the corresponding weights of all samples.

For the determination of the material composition, manual sorting was performed to particle size ranges ≥10 mm following the procedure described by the German guideline for uniform waste analysis in Saxony (Richtlinie zur einheitlichen Abfallanalytik in Sachsen). Grouped material fractions, such as "Combustibles" (i.e. "3D plastics", "2D plastics", "Textiles", "Wood", "Leather" and "Paper, Paperboard and Cardboard (PPC)"), "Inert" (i.e. "Bricks/Concrete/Stones", "Ceramics" and "Glass"), "Total metals" (i.e. "Fe metals" and "Non-Fe metals"), "Others" (i.e. bones, shells, sponges and unidentifiable materials), "Agglomerated fines <10 mm" (i.e. material <10 mm that stuck together due to the presence of moisture and formed material agglomerates) and "Fine fractions <10 mm" (i.e. soil, organic and weathered inert materials) were employed for the classification of the material composition.

3. RESULTS AND DISCUSSION

A total amount of about 374 Mg of waste was excavated and pre-processed at the MSG landfill, from which around 77 wt.% (raw state) corresponded to the fine fractions. The excavated pit (Figure 1d) had a total volume of about 425 m^3. As described in Section 2.2, the excavated volume was divided into four batches, which were about 140 m^3 (batch 1), 100 m^3 (batch 2), 120 m^3 (batch 3) and 65 m^3 (batch 4). Batch 1 and batch 2 consisted mainly of a mixture of MSW and C&D (Figure 5a,b), while batch 3 (Figure 5c) and batch 4 (Figure 5d) were mostly composed of C&D and MSW, respectively.

The total weights of the excavated batches in raw state were about 111 Mg for batch 1, 59 Mg for batch 2, 149 Mg for batch 3 and 55 Mg for batch 4, from which about 80 wt.%, 76 wt.%, 73 wt.% and 80 wt.% corresponded to

FIGURE 5: Fine fractions in raw state - a) batch 1, b) batch 2, c) batch 3 and d) batch 4.

the fine fractions, respectively. Table 1 summarizes the amounts and characteristics of the fine fractions obtained of each batch from the mechanical pre-processing.

The total mass and volume of the excavated material, as well as of the obtained fine fractions were determined by means of the articulated trucks and weighing bridge. Bulk density, water content, PSD and material composition were determined from the analysis of composite samples at IAR´s technical facility.

3.1 Bulk density and water content

Bulk density and water content are key parameters for the design of an effective and efficient mechanical processing of fine fractions, since the type of processing methods (i.e. processing approach) and size/number of processing units to be employed depend on them to a great extent. Hence, both bulk density and water content belong to the foremost parameters to be determined from fine fractions in (E)LFM. To this end, an amount of eight composite samples (n=8) was used to determine the bulk density in the raw state of each batch. The results were used to calculate different percentiles, as percentiles are a useful measure to identify the variation range in a set of values, while excluding a certain percentage of them that are less likely to occur according to pre-selected low and high limits. The 25th, 50th (median) and 75th percentiles were found to be the most useful for depicting the fluctuations of the bulk density. These results, together with the

TABLE 1: Amounts of excavated waste and fine fractions in raw state.

Batch	Material type	Amount of excavated waste [Mg]	Volume of excavated waste [m³]	Amount of fine fractions from excavated waste [wt.%]
1	MSW + C&D	111	140	80
2	MSW + C&D	59	100	76
3	Mostly C&D	149	120	73
4	Mostly MSW	55	65	80
	Total	374	425	77

maximum and minimum values, are shown as box-and-whisker plots in Figure 6a.

Results show that the bulk densities of batches 1 and 2 were quite similar, while those of batches 3 and 4 were very different from each other. Batch 3 presented a median bulk density around 1230 kg/m^3, which is comparable to that of C&D, with a very narrow variation between 25th and 75th percentiles accounting for the homogeneity of the material. Batch 4 had a median bulk density of about 630 kg/m^3, which corresponds to that of MSW, with a wider variation between 25th and 75th percentiles accounting for the heterogeneous nature of MSW. The determined bulk densities of batches 1 and 2 were located in between those of batches 3 and 4 with medians around 850 kg/m^3 (batch 1) and 810 kg/m^3 (batch 2) and a stronger overall variation between 25th and 75th percentiles, which logically correlates to a mixture of both C&D and MSW. In general, the bulk density of the fine fractions (all batches) varied between 720 kg/m^3 and 1000 kg/m^3 with a median of about 810 kg/m^3.

Regarding water content, four composite samples (n=4) were used to determine the moisture content of each batch, since the remaining amount of composite samples were used to determine the material composition in raw state. Analogously to bulk density, the 25th, 50th and 75th percentiles, and the maximum and minimum values of the water content were used to plot the corresponding box-and-whisker diagrams, which are displayed in Figure 6b.

Batches 1 and 2 showed very similar results with regard to water content, both with medians of about 27 wt.% and very slight variations between 25th and 75th percentiles. On the contrary, batches 3 and 4 presented water content medians of around 18 wt.% and 37 wt.%, respectively, with relatively larger variations between 25th and 75th percentiles. Altogether, the water content of the fine fractions had a median of about 27 wt.% and fluctuated between 25 wt.% and 30 wt.%. Thus, an overall bulk density range of 720-1000 kg/m^3 and a total water content range of 25-30 wt.% can be used to describe the fine fractions of MSG landfill.

Additionally, four (n=4) and eight (n=8) composite samples were used to determine the variation of bulk density with particle size in raw and dry states, respectively. This information is plotted in Figure 7, in which it can be observed that bulk density had slight variations between particle sizes of 1 mm and 6 mm, but strong ones between 6 mm and 90 mm in both states. The curves for raw state (shown in blue in Figure 7) begin at 1 mm because in this state particle sizes mostly <1 mm tend to adhere to each other and form agglomerates with diameters above 1 mm. From these results it can be said that, practically, bulk density decreased as particle size increased for both raw and dry states. Nonetheless, a decrease in bulk density was observed below 0.16 mm in dry state, probably because most of the remaining materials with high densities, such as ceramics, stones, glass and metals, were found above that particle size range.

The comparison of the medians of the raw data between raw and dry states, for several particle size ranges, reveals that bulk density decreased about 12% in the particle size range between 90-63 mm, 30% in 63-31.5 mm, 33% in 31.5-10 mm, 21% in 10-6.3 mm, 23% in 6.3-3.15 mm and 16% in 3.15-1 mm after drying with respect to raw state. The overall median of the reduction in bulk density of the fine fractions after drying was around 21%, which can be very useful information for the design of the mechanical processing.

Furthermore, four composite samples (n=4) from each of the batches 1, 3 and 4 after manual characterization were used to determine the water content per type of material, for three particle size ranges (90-63 mm, 63-31.5 mm

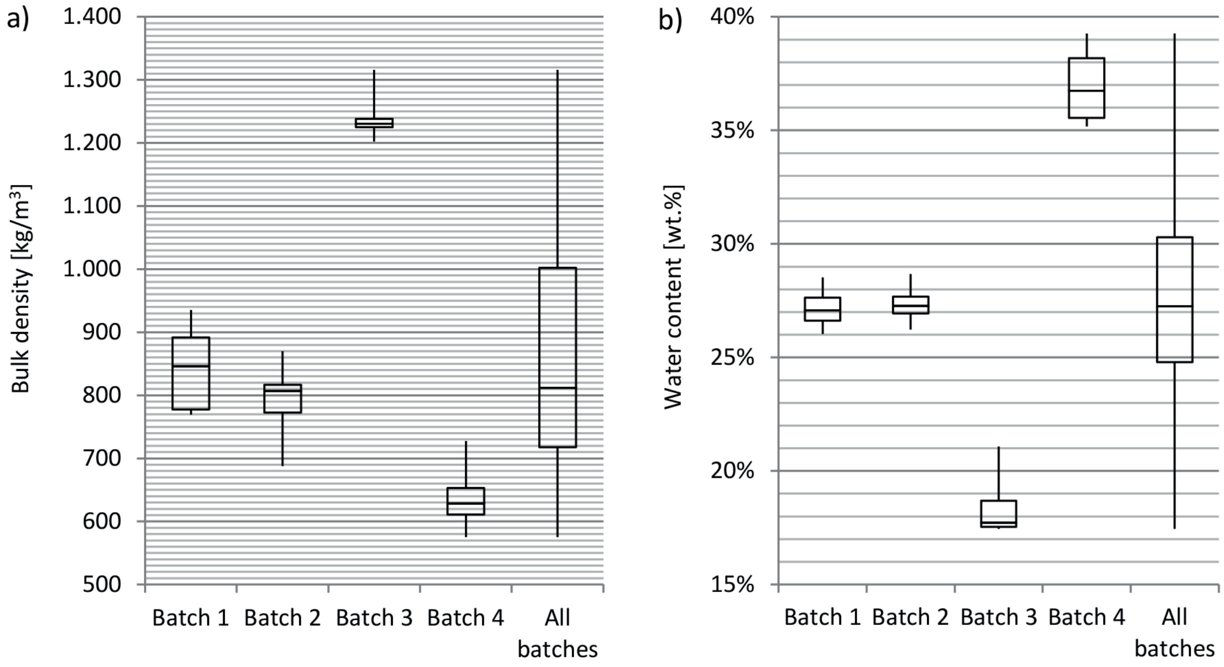

FIGURE 6: a) Bulk density in raw state and b) water content of the fine fractions.

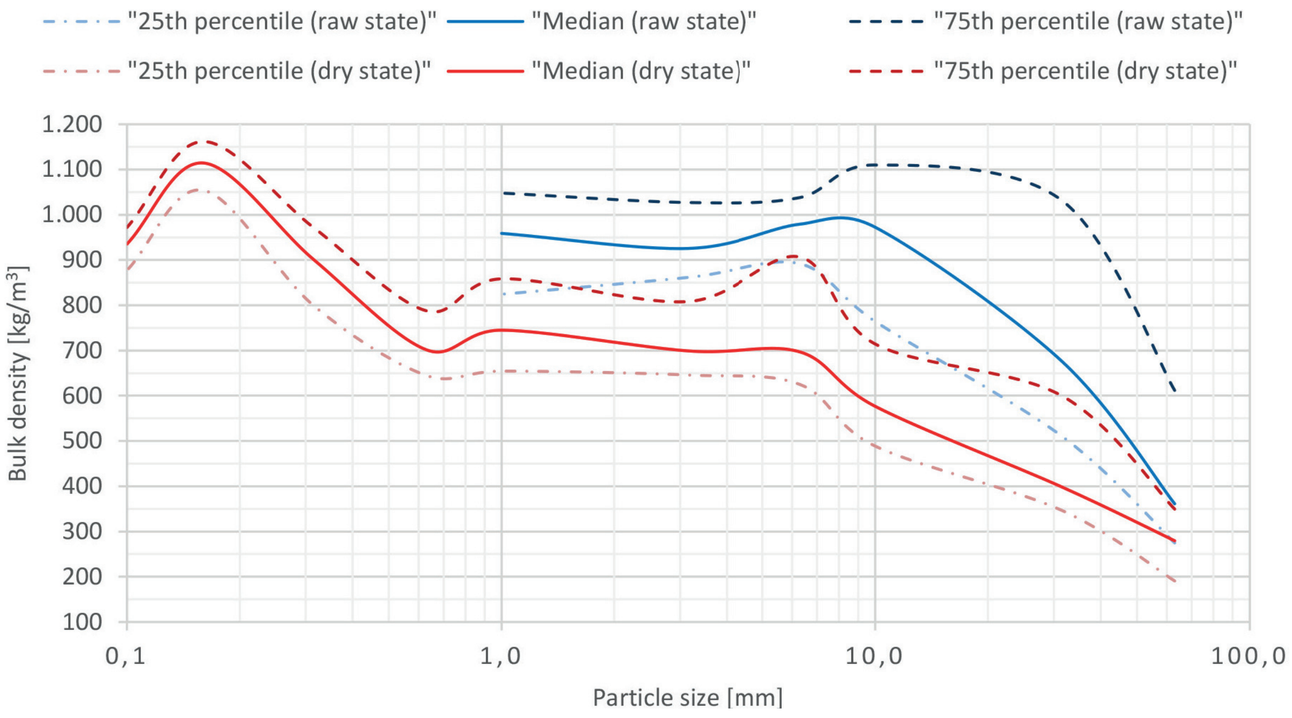

FIGURE 7: Variation of bulk density with particle size in the fine fractions in raw (blue) and dry (red) states.

and 31.5-10 mm), in order to study the water distribution among them. This information is shown in Table 2.

The materials presented in Table 2 can be classified into those with high, medium and low water contents. "PPC" and "Wood" showed the highest values, while "Bricks/Concrete/stones", "Ceramics", "Glass", "Fe metals" and "Non-Fe metals" presented the lowest values. Despite being among the materials with the lowest water content, "Ceramics", "Glass", "Fe metals" and "Non-Fe metals" show considerable amounts of water, which can be explained by the presence of impurities. In this case study impurities are regarded as fine particles (mainly <1 mm) of organic and inorganic matter that attach to the surface of coarser particles (also known as surface defilements). Impurities are

TABLE 2: Water content per material type of the fine fractions 90-10 mm.

Material type	Particle size range								
	90-63 mm			63-31.5 mm			31.5-10 mm		
	25th percentile	Median	75th percentile	25th percentile	Median	75th percentile	25th percentile	Median	75th percentile
3D plastics	16.2	19.9	25.2	20.3	22.5	27.3	18.3	20.5	24.2
2D plastics	18.4	26.4	34.4	25.8	31.4	33.2	24.4	27.8	32.7
Leather	N.A.	N.A.	N.A.	11.5	20.3	29.0	8.1	12.6	16.2
PPC	55.1	60.4	63.4	54.6	57.8	59.3	45.9	50.8	53.9
Textiles	26.9	32.9	34.6	22.3	33.7	39.1	22.6	26.3	30.6
Wood	57.8	60.1	60.7	53.1	56.1	59.7	43.7	47.2	56.0
Bricks/Concrete/ Stones	8.4	12.3	12.6	12.7	13.5	14.2	14.4	15.4	16.4
Ceramics	4.5	5.8	7.0	3.0	4.6	6.3	2.2	6.2	13.2
Glass	0.0	0.0	0.0	0.9	2.1	3.1	3.3	3.7	5.0
Fe metals	0.2	0.3	0.7	3.2	5.3	8.9	3.1	8.8	13.7
Non-Fe metals	0.5	1.0	1.4	1.5	5.8	8.6	2.5	10.0	15.5
Others	43.9	45.9	48.0	17.8	21.5	37.3	19.8	23.7	31.0
Agglomerated fines <10 mm	19.5	27.8	29.8	25.7	32.6	39.1	21.7	29.1	38.5

Notes: Figures are given in wt.%. Materials for which no sample was obtained are denoted as not available (N.A.).

associated with an increase of water content due to their capability to absorb and adsorb water. “3D plastics” and “2D plastics”, “Leather”, “Textiles”, as well as “Others” and “Agglomerated fines <10 mm”, belong to the materials with medium water contents. Similarly to “Ceramics”, “Glass”, “Fe metals” and “Non-Fe metals”, the moderate water contents of “3D plastics” and “2D plastics” are most likely to be due to the presence of impurities. This type of information results very useful during the design of the mechanical processing, as the effectivity of density separation methods can be greatly influenced by by the water content.

Moreover, no conclusive trend was identified regarding water content and particle size range, except for “Glass”, “Fe metals” and “No-Fe metals”, whose water contents increased as the particle size range decreased. The latter can be explained by the fact that the impurities vs. material type mass-ratio increases with the reduction in particle size of the material type.

After sieving in raw state, four composite samples (n=4) from each of the batches 2, 3 and 4 were employed for the determination of the water content per particle size range, which allowed to identify if some tendency of water being retained by a certain particle size range was to be found. This information was correlated with the mass distribution throughout the particle size ranges in question, so that its influence in the water distribution could be studied as well. This correlation is depicted in Figure 8.

Figure 8 shows that the water content was more or less evenly distributed throughout the fine fractions, as well as that most of the material and water were concentrated in the particle size range 31.5-10 mm. It is important to emphasize that the presence of water, up to a certain extent, promoted the formation of agglomerates and increased the amount of surface defilements and, therefore, a relevant amount of small particle sized material (mainly <1 mm) was retained in bigger particle size ranges when the fine fractions were in raw state (i.e. in the presence of moisture).

3.2 PSD analysis

The PSD analysis determines the amount of material in a certain particle size/particle size range with respect to the total amount of material. Among bulk density and water content, PSD is of critical importance for the design of an adequate processing approach of the fine fractions, as it gives information about the distribution of the material throughput in particle size classification steps of the mechanical processing, which are required for an effective and efficient mechanical processing. Hence, the PSD of the fine fractions was determined for both raw and dry states, in which four composite samples (n=4) from each batch were analyzed for each state. The obtained data from all batches was studied as a whole to produce and analyze the overall PSD curves of the fine fractions in both raw and dry states. This information is presented (Figure 9) using the 25th, 50th and 75th percentiles in order to show the median and variation range of the PSD, as well as to allow direct comparison between both states.

As displayed in Figure 9, the material in dry state presented a more uniform PSD than in raw state, since, as already mentioned, in moist conditions (raw state) fine particles, mostly <1 mm, tend to form agglomerates and adhere to coarser particles as surface defilements. Taking the curve for dry state as a reference for the real PSD of the fine fractions, it can be said that water content substantially influences the PSD of the material in a direct way and,

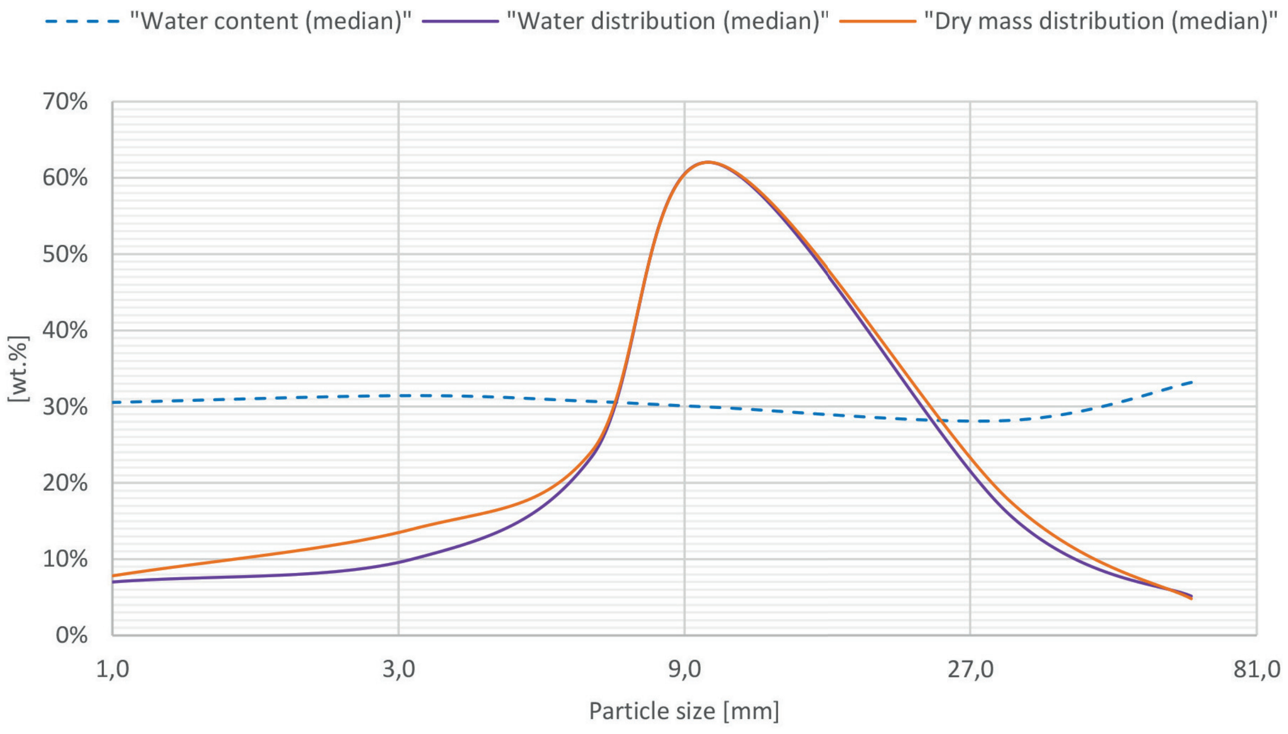

FIGURE 8: Water content, water and dry mass distribution in the fine fractions.

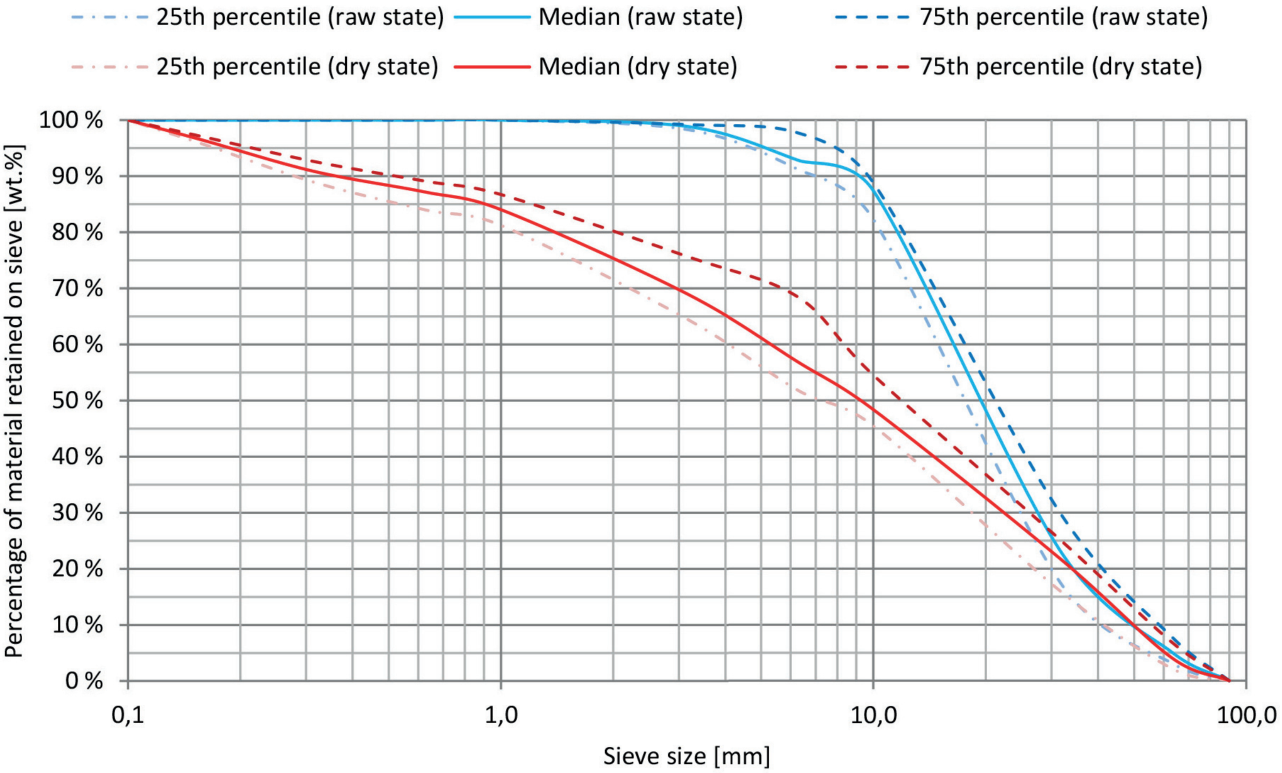

FIGURE 9: PSD of the fine fractions in raw (blue) and dry (red) states.

thus, the performance of sieving steps throughout the mechanical processing as well.

Moreover, about 80-90 wt.% of the fine fractions in raw state and around 45-55 wt.% in dry state were retained on the 10 mm sieve. On the contrary, fine fractions presented slighter differences between raw and dry states, regarding sieving performance, on the 31.5 mm sieve, in which 18-30 wt.% was retained in raw state and 16-25 wt.% in dry state. Therefore, it can be concluded that the PSD analysis of the fine fractions in raw and dry states can be useful to identify the required number and optimal cut-off diameter size of the sieving steps of the mechanical processing. Additionally, the PSD analysis can be used to identify the optimal moisture content to process the fine fractions in a dry mechanical processing in order to minimize dust generation and material loss, while maintaining a high sieving efficiency and without the need of complete drying. Besides, the PSD analysis can be employed to pinpoint the particle size from which the material might require a drying step or wet processing.

For example, in this case an initial sieving down to around 30 mm could be performed to the fine fractions directly after the ballistic separation process, without the necessity of any drying step. Nevertheless, the impact of processing the excavated material in raw state on the quality (amount of impurities and surface defilements) of the fractions to be subsequently recovered from both coarse and fine fractions needs to be taken into account for this as well. Subsequently, the moisture content of the material <30 mm could be either reduced or increased, according to the succeeding mechanical processing method (i.e. dry or wet), before applying an additional sieving at about 10 mm. The moisture adjustment would serve the purpose of increasing the sieving efficiency, reducing the amount of material agglomerates and surface defilements and, hence, improving the performance of the following mechanical processing.

3.3 Material composition

Besides bulk density, water content and PSD, the material composition of the fine fractions is of decisive relevance for the design of an appropriate mechanical processing approach, as well as for the selection of the WtM and WtE strategies to follow. The types of materials that could be recovered from the fine fractions are identified by the determination of the material composition and, in combination with PSD analysis, it provides information regarding the amount and location, in terms of particle size range, of the materials to be recovered, as well as information required for selecting an adequate processing method. Thus, the material compositions of batches 1, 3 and 4 were determined in both raw and dry conditions from a total of four composite samples (n=4) for each batch and state. Photographs of the material types that constitute the grouped material fractions (i.e. “Combustibles”, “Inert”, “Total metals”, “Others” and “Agglomerated fines <10 mm”) defined in Section 2.3 are displayed in Figure 10. Due to strong similarities between batches 1 and 2 regarding visual material composition, bulk density, water content and PSD, the composition of batch 1 has been assumed valid for batch 2 as well. The composite samples of batch 2 were used to obtain additional information, such as the variation of bulk density and water content according to particle size, which modified the initial conditions of the material and, thus, did not allow obtaining reliable results if manual sorting were to be performed a posteriori. The data obtained from the material characterization of batches 1, 3 and 4 was, hence, used to calculate the median material composition of the fine fractions as a whole.

In order to allow direct comparison between the results

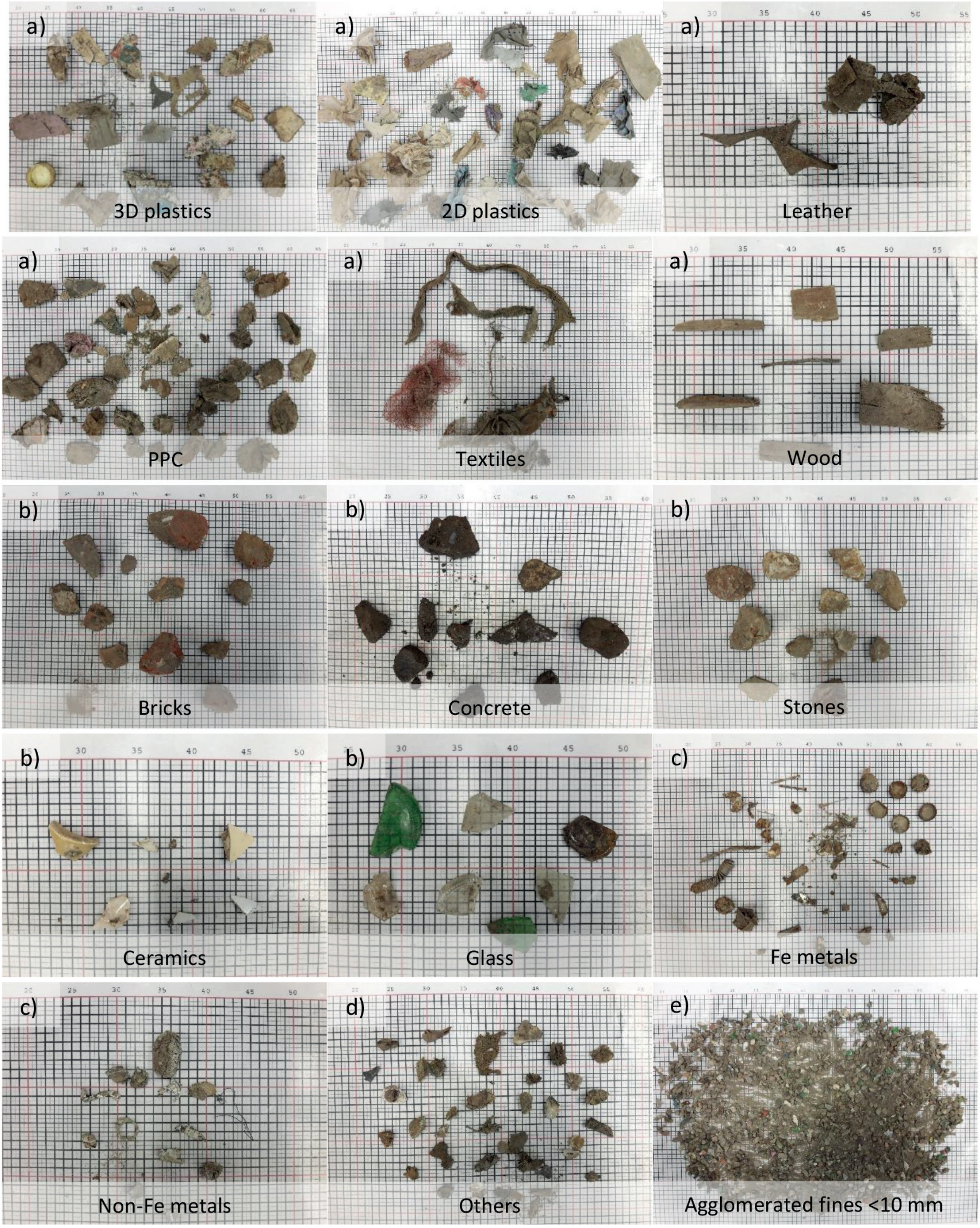

FIGURE 10: Photographs of the grouped material fractions: a) “Combustibles”, b) “Inert”, c) “Total metals”, d) “Others” and e) “Agglomerated fines <10 mm”.

of raw and dry states, the water content of each material type was determined and deducted from the results of the material composition in raw state (i.e. raw state in water-free conditions). In this way, the capacity of some materials to absorb and adsorb water does not play a role in the results of weight distribution, which could lead to relevant misinterpretations in some cases.

The results of the material composition, classified in five grouped material fractions (i.e. "Combustibles", "Inert", "Total metals", "Others" and "Agglomerated fines <10 mm") and according to the three particle size ranges (i.e. 90-63 mm, 63-31.5 mm and 31.5-10 mm), for raw, raw (water-free) and dry states are presented in Table 3. The material composition of the "Fine fractions <10 mm" was not determined in this study and, thus, this fraction was included in Table 3 as "Mixed materials". It was visually detected that the fine fractions <3.15 mm in both states mostly corresponded to a relatively homogeneous soil-like material, which in turn was mainly composed of weathered inorganic and degraded organic matter. The presence of "Combustibles", "Total metals" and "Others" could not be identified below 3.15 mm.

The overall material composition of the fine fractions showed amounts of "Agglomerated fines <10 mm" of about 1.1 wt.% and 1.1 wt.% in the particle size range 90-63 mm, 1.7 wt.% and 1.5 wt.% in 63-31.5 mm and 35.4 wt.% and 34.2 wt.% in 31.5-10 mm in raw and raw (water-free) states, respectively. The amounts of the same fraction in dry state were around 0.1 wt.% in the particle size range 90-63 mm, 0.2 wt.% in 63-31.5 mm and 3.5 wt.% in 31.5-10 mm, which means that the amount of agglomerated material is roughly ten times lower in dry state than in raw and raw (water-free) states. In turn, "Fine fractions <10 mm (Mixed materials)" presented an amount of about 12.3 wt.% and 11.8 wt.% in raw and raw (water-free) states, respectively, versus around 51.8 wt.% in dry state. This information confirms that a significant amount of "Fine fractions <10 mm" tends to form agglomerates and adhere to bigger particles in raw state (presence of moisture), which end up mixed with and adhered to coarser material fractions (i.e. "Combustibles", "Inert", "Total metals" and "Others"), potentially leading to a reduction in efficiency and performance along the mechanical processing. For instance, the variation of the amounts of "Total metals" between raw, raw (water-free) and dry states are likely to be mainly attributed to the presence of surface defilements, which still remained attached to that fraction after drying in most of the samples.

The presence of surface defilements was visually identified in the "Combustibles", "Inert", "Total metals" and "Others" fractions in raw, raw (water-free) and dry states. As it can be logically expected, the amount of surface defilements was considerably larger in raw and raw (water-free) states than in dry state. It is important to point out that the material composition to be taken as a reference in (E)LFM projects and investigations regarding material and energy recovery is the one determined in dry state, since in this state the material composition is least influenced by the presence of water, agglomerates and surface defilements

TABLE 3: Material composition of the fine fractions per particle size range in raw, raw (water-free) and dry states.

Particle size range / Grouped material fraction		Amount [wt.%]								
		Raw state			Raw state (water-free)			Dry state		
		25th percentile	Median	75th percentile	25th percentile	Median	75th percentile	25th percentile	Median	75th percentile
90-63 mm	Combustibles	0.6	1.1	3.6	0.5	0.9	3.2	0.3	1.0	3.0
	Inert	0.1	1.4	2.2	0.2	1.6	2.5	0.9	1.5	2.9
	Total metals	0.0	0.0	0.2	0.0	0.0	0.2	0.0	0.0	0.2
	Others	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Agglomerated fines <10 mm	0.4	1.1	1.9	0.4	1.1	1.7	0.0	0.1	0.1
63-31.5 mm	Combustibles	2.4	5.9	8.0	1.9	4.7	5.9	0.7	2.7	6.4
	Inert	5.6	7.6	8.0	7.2	8.5	9.9	8.7	9.7	13.2
	Total metals	0.0	0.4	0.7	0.0	0.4	0.9	0.2	0.7	0.9
	Others	0.1	0.3	0.8	0.1	0.4	0.8	0.0	0.2	1.6
	Agglomerated fines <10 mm	0.6	1.7	9.7	0.6	1.5	9.0	0.2	0.2	0.3
31.5-10 mm	Combustibles	2.9	3.7	12.4	2.5	3.2	9.4	1.3	3.7	9.6
	Inert	9.4	12.3	20.4	13.2	16.8	21.7	17.8	19.9	22.2
	Total metals	0.3	0.4	0.6	0.4	0.6	0.7	0.3	0.5	0.7
	Others	0.6	0.8	5.4	0.6	0.8	5.8	0.4	0.6	1.1
	Agglomerated fines <10 mm	25.5	35.4	42.0	23.9	34.2	41.0	2.9	3.5	3.8
Fine fractions <10 mm	Mixed materials	11.3	12.3	15.3	11.1	11.8	14.6	37.8	51.8	55.6

and, hence, reflects the material composition which is closest to reality. Therefore, discrepancies from the material composition in raw state with respect to the one in dry state can be explained by the presence of impurities and moisture. The latter being valid only if the quantities have not been calculated under water-free conditions. Nevertheless, more precise results of material composition might be achieved by implementing a washing step or wet sieving before the manual characterization, which will most likely require additional effort and time. The determination of the material composition in raw and raw (water-free) states is useful for the quantification and localization of material agglomerates and impurities, which are of critical relevance for the design of the mechanical processing.

In the case of the “Inert” fractions, amounts of about 1.4 wt.% and 1.6 wt.% in the particle size range 90-63 mm, 7.6 wt.% and 8.5 wt.% in 63-31.5 mm and 12.3 wt.% and 16.8 wt.% in 31.5-10 mm were determined in raw and raw (water-free) states, while amounts of 1.5 wt.%, 9.7 wt.% and 19.9 wt.%, respectively, were obtained in dry state. These figures show that most of the “Inert” fraction was found between 31.5 mm and 10 mm in all three states and that the amount of “Inert” increased with the decrease in particle size. Nonetheless, the influence of moisture (agglomerates and surface defilements) might lead to misinterpretations if not taken into account properly, considering that the real amount of “Inert” is higher than the one shown by the compositions in raw and raw (water-free) states.

The amounts of “Combustibles” and “Others” showed inconsistent fluctuations between the different states and particle size ranges, which might be explained due to the fact that both correspond to the most heterogeneous grouped fractions and are composed of various materials with different properties.

The previous outcomes show that “Total metals” were less affected, in terms of impurities, by the presence of moisture and, therefore, they could be recovered in raw state of the fine fractions, provided that the original water content allows an effective particle size classification (sieving) a priori. On the other hand, other fractions, such as “Combustibles” and “Inert” fractions, might need either partial/complete drying or washing step before material recovery can be implemented efficiently.

In general, these results show that most of the amount of the grouped fractions is located between 63 mm and 10 mm and, therefore, omitting the sieving step at 63 mm and sieving directly at around 30 mm would be advisable for full scale processing of the fine fractions. Particle size classification, as well as most mechanical processing steps in (E)LFM, performs best with narrow differences in particle sizes, so a direct sieving from 90 mm to 10 mm would most likely lead to sieve clogging and bad performance of the equipment along the subsequent mechanical processing.

3.4 Potential for material and energy recovery

The findings presented above document the presence of materials in the fine fractions that could have potential for WtM and WtE (i.e. “Combustibles”, “Inert” and “Total metals”), as well as the most important characteristics of the fine fractions (i.e. bulk density, water content and PSD) that are to be taken into account for the design of an effective and efficient mechanical processing. Provided that such mechanical processing is implemented, the fine fractions from the excavated area at MSG landfill could yield medians of about 8.0 wt.% “Combustibles”, 32.4 wt.% “Inert”, 1.3 wt.% “Total metals”, 0.9 wt.% “Others”, 3.8 wt.% “Agglomerated fines <10 mm” and 51.8 wt.% “Fine fractions <10 mm” (Table 4). As the fraction “Others” was mostly composed of organic matter (e.g. bones, shells, sponges, among others), which could be valorized thermally together with the “Combustibles” fraction, the total amount of combustibles could be slightly increased.

If processed in dry or reduced moisture state (optimal water content) most of “Agglomerated fines <10 mm” would most likely end up in the “Fine fractions <10 mm”, raising the amount of the latter as well. This fraction could be processed further in order to recover additional amounts of “Combustibles”, “Inert” and “Total metals”, since it was identified through PSD analysis and manual characterization that some of those material fractions were still present above 3.15 mm. These additional amounts are most likely to be low; nonetheless, this is a necessary step in order to reduce the amount of undesired materials if the production of a soil substitute material is envisaged. As proposed in Hernández Parrodi et al., 2018b, “Fine fractions <10 mm” could be processed further to produce a material that can be used as soil substitute in construction applications, whereas the “Inert” fraction could be used for the production of construction aggregates and “Total metals” could be sent to recycling, following the WtM pathway. In turn, “Combustibles” (together with “Others”) could be suitable to produce refuse derived fuel (RDF) and, thus, incorporate to a WtE scheme. Nonetheless, the mechanical processing approach is to be designed in such a way that the applicable specifications for the usage of such materials in the intended purposes are met as well.

It is relevant to note that the previous amounts were taken directly from the results of the manual characterization and PSD analysis without considering efficiencies of mechanical processing and material losses. Therefore, these figures may vary considerably in full scale processing.

TABLE 4: Material composition of the fine fractions in dry state.

Particle size range / Grouped material fraction		Amount [wt.%]		
		25th percentile	Median	75th percentile
Fine fractions 90-10 mm	Combustibles	2.1	8.0	19.7
	Inert	31.1	32.4	35.4
	Total metals	0.6	1.3	1.8
	Others	0.6	0.9	3.4
	Agglomerated fines <10 mm	3.3	3.8	4.2
Fine fractions <10 mm	Mixed materials	37.8	51.8	55.6

4. CONCLUSIONS

The determination of the main characteristics of the fine fractions, such as bulk density, water content, PSD and material composition, is of utmost importance for the design of a successful mechanical treatment process, as well as for assessing the potential for material and energy recovery from fine fractions in (E)LFM projects. Bulk density, water content, PSD and material composition, as well as the correlations between them, are necessary information in order to be able to predict the behavior of fine fractions in a certain mechanical processing method. Furthermore, they turn out to be critical parameters to be taken into account for an appropriate selection of processing methods. Moreover, material composition serves as a basis to identify the strategies to follow regarding WtM and WtE in (E)LFM.

In this case study about 77 wt.% of the total landfill-mined material in raw state corresponded to the fine fractions (material <90 mm), which had an overall bulk density range of 720-1000 kg/m^3 and a total water content range of 25-30 wt.%. In general, bulk density appeared to increase as particle size decreased in both raw and dry states. Nevertheless, a decrease in bulk density was observed in the particle size range <0.16 mm in dry state. Furthermore, the overall bulk density was reduced about 21 wt.% after drying the fine fractions, which can be very useful information for the design of the mechanical processing.

The amount of moisture contained in the fine fractions substantially influences the presence of “Agglomerated fines <10 mm”, as well as the amount of impurities in the fractions “Combustibles”, “Inert”, “Total metals” and “Others”. “Total metals” seemed to be less influenced by water content and, therefore, their recovery could be done in raw state, given that the original water content allows an adequate particle size classification a priori. For the recovery of the “Combustibles”, “Inert” and “Others” fractions and further processing of the “Fine fractions <10 mm”, additional drying/moisture reduction or washing step/wet processing might be required in order to achieve adequate mechanical processing and obtain acceptable material qualities.

In addition to the determination of the relative mass distribution according to size, the PSD analysis in both raw and dry states can be used to identify the particle size from which the fine fractions might require a drying step or wet processing. Moreover, such analysis can also be utilized to determine the optimal water content in order to minimize dust generation and material loss during dry mechanical processing without the need of complete drying.

Results on the material composition in dry state reveal that amounts of 2.1-19.7 wt.% “Combustibles”, 31.1-35.4 wt.% “Inert” and 0.6-1.8 wt.% “Total metals” could be recovered from the fine fractions 90-10 mm, while 37.8-55.6 wt.% “Fine fractions <10 mm” could be processed further in order to increase the recovery amounts of the previous fractions and produce a substitute material for soil in construction applications. For this, applicable specifications for the usage of such materials in the foreseen purposes need to be taken into account.

It is highly important to highlight that the findings of this study are only valid for the investigated area at the landfill site and, therefore, additional studies covering the complete landfill area of the site are to be done in order to determine the overall material composition and characteristics of the MSG landfill, as well as to assess the global potential for WtM and WtE. Additionally, it is of critical relevance to point out that one of the greatest challenges faced by (E)LFM remains to be the processing of the fine fractions for the recovery of valorizable fractions in an economically feasible manner, since the implicated capital and operating expenditures continue to outweigh the revenues obtained by the valorization of those fractions. However, this situation is more related to policy and market aspects than to its technical feasibility.

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7 MONT-SAINT-GUIBERT CASE STUDY: MECHANICAL PROCESSING OF THE FINE FRACTIONS

Scientific article no. 6: “Case Study on Enhanced Landfill Mining at Mont-Saint-Guibert Landfill in Belgium: Mechanical Processing of Fine Fractions for Material and Energy Recovery”

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Annotation on my personal contribution to this scientific article:

According to the results of the scientific article no. 5 and in consultation with Karoline Raulf, Daniel Vollprecht, Thomas Pretz and Roland Pomberger, I designed and planned the mechanical processing approach to be applied to the fine fractions. The tests were carried out by me with assistance provided by Karoline Raulf, Daniel Vollprecht, Thomas Pretz and Roland Pomberger, who also facilitated most of the necessary equipment to perform them. The analysis of the results and their evaluation was conducted in collaboration with all authors, as well as the review of the whole article. The revision was done by me.

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CASE STUDY ON ENHANCED LANDFILL MINING AT MONT-SAINT-GUIBERT LANDFILL IN BELGIUM: MECHANICAL PROCESSING OF FINE FRACTIONS FOR MATERIAL AND ENERGY RECOVERY

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ABSTRACT

(Enhanced) landfill mining ((E)LFM) projects have been mainly driven by land reclamation, environmental pollution mitigation and remediation of old landfills and dumpsites, among others. However, previous studies have also shown that these sites may be a relevant source of secondary raw materials. In this respect and within the framework of the "EU Training Network for Resource Recovery through Enhanced Landfill Mining – NEW-MINE", around 374 Mg of waste was excavated from a landfill site in the municipality of Mont-Saint-Guibert, Belgium, as part of a case study to evaluate the full implementation of ELFM. The excavated landfilled material was pre-processed with a ballistic separator onsite directly after excavation, with which the fine fractions (material <90 mm) were obtained. Subsequently, samples of the fine fractions were characterized in order to determine their main properties and material composition, which in turn were used to define the material and energy recovery strategies to be followed. According to these strategies a chain of mechanical processing steps was selected and tested in the processing of the fine fractions in the optimal water content (15 wt.% WC) and dry states. The mechanical processing consisted of particle size classification, ferrous and non-ferrous metals extraction, density separation and sensor-based sorting steps. For the recovery of materials (waste-to-material), fractions of a soil-like material (fine fractions <4.5 mm), inert, ferrous and non-ferrous metals were targeted. These fractions might be suitable for replacing soil in construction applications (e.g. embankments), substituting construction aggregates (e.g. construction gravel) and recycling, respectively. For the recovery of energy (waste-to-energy), a fraction composed of combustible materials was aimed for, which might be suitable for the production of an alternative fuel (e.g. refuse derived fuel). The mechanical processing in the dry state yielded total amounts of 41.9-43.9 wt.% DM fine fractions <4.5 mm, 35.9-39.0 wt.% DM inert materials, 7.4-10.0 wt.% DM combustible materials, 1.2-1.8 wt.% DM ferrous metals and 0.2-0.4 wt.% DM non-ferrous metals. These figures suggest that a significant share of the fine fractions could be recovered through the tested mechanical processing approach, which might contribute to the overall economic and environmental feasibility of the project in case of implementing full scale (E)LFM at the studied landfill site.

1. INTRODUCTION

Early research shows that (enhanced) landfill mining ((E)LFM) projects have been mainly driven by land reclamation, environmental pollution mitigation and remediation of old landfills and dumpsites, among others (Hernández Parrodi, Höllen, & Pomberger, 2018a). However, many LFM projects have faced strong difficulties or even failed to achieve immediate economic feasibility, which does not take into account long-term environmental passive costs, such as landfill aftercare and air, water and soil pollution remediation, among others. Furthermore, this has been frequently accompanied by social, political and legislatorial resistance, despite the pollution remediation and mitigation nature of LFM. Altogether, such circumstances have created skepticism towards the viability of the LFM concept and hampered its widespread practice. Therefore,

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LFM has evolved over the last decade into a sound concept known as ELFM, which seeks to meet the environmental, social and economic constraints in LFM; incorporating maximum material and energy recovery, while complying with the most stringent environmental and social criteria (Jones, Geysen, Rossy, & Bienge, 2010). Within the framework of ELFM, a research project from the European Union started in 2016 and has been studying the full implementation of this concept. This project is the "EU Training Network for Resource Recovery through Enhanced Landfill Mining – NEW-MINE", which studies, among others, additional sources of revenue, such as high value-added products (i.e. hydrogen, methane, synthetic polymers and glass ceramics), as well as the involved social, environmental and policy implications to promote not only economic but overall feasibility of ELFM and its successful implementation in current waste management systems (Hernández Parrodi et al., 2019b).

NEW-MINE is related to a handful of landfill sites in Europe, including the Mont-Saint-Guibert (MSG) landfill in Belgium. The latter was chosen to perform the assessment of a whole case study on ELFM. Landfill waste was excavated from the MSG landfill and pre-processed onsite directly after excavation. Two ballistic separation steps were employed as pre-processing, in which the excavated material was divided into different outputs. The relevant output stream for the present study are the fine fractions, which was the material with a particle size <90 mm obtained after the second step of ballistic separation. Representative single samples were taken at the underscreen outlet of the ballistic separator. Those single samples were used to prepare composite samples, which were employed to perform the material characterization of the fine fractions reported in Hernández Parrodi et al., 2019a. According to the results of the material characterization, the waste-to-material (WtM) and waste-to-energy (WtE) strategies for the fine fractions were defined and a specific mechanical processing approach was selected.

The main purpose of the selected mechanical processing was to separate the fine fractions into five different fractions: combustibles, inert, ferrous (Fe) metals, non-ferrous (non-Fe) metals and fine fractions <4.5 mm. Combustibles were intended to produce a fraction with high calorific value that could be used as refuse derived fuel (RDF). This type of material recovered from old landfill sites is usually very heterogenous and presents undesired characteristics for traditional recycling, such as significant water content, great amount of impurities and high state of degradation. Hence, thermo-chemical processes (i.e. incineration, gasification and pyrolysis) might result to be some of the few presently available and feasible alternatives to valorize landfill-mined materials with high calorific value, transforming them into a potential source of energy for WtE applications. Inert, Fe and Non-Fe metals, as well as the fine fractions <4.5 mm, targeted towards WtM. The recovery of Fe and non-Fe metals was envisaged for recycling, while the production of a substitute for construction aggregates was foreseen with the inert fraction. A substitute for soil in construction applications was targeted with the fine fractions <4.5 mm.

To this end, composite samples of the fine fractions from the MSG landfill were processed with a series of mechanical processing equipment. The equipment employed, as well as the results obtained are presented herein. The main objective of this study is to evaluate and discuss the performance of the selected mechanical processing approach for optimum material and energy recovery in (E)LFM.

2. MATERIALS AND METHODS

2.1 Site description, excavation works and material pre-processing

The landfill site "Centre d´enfouissement Technique de Mont-Saint-Guibert (CETeM)" is located in the municipality of MSG in Wallonia, Belgium, about 33 km south of Brussels capital city. This landfill was one of the main disposal sites of municipal solid waste (MSW), non-hazardous industrial waste (IW) and construction and demolition waste (C&D) in the province of Walloon Brabant from 1958 to 2014 (Bureau d´études greisch (beg), 2002). For this investigation about 425 m^3 (374 Mg) of landfill waste were excavated (~10 m long, ~10 m wide and ~4 m deep) and the excavated volume was divided into four sub-volumes, which are henceforth referred to as batches. These batches were visually classified according to their main composition, as a clear stratification of the material was identified during excavation. The C&D and MSW layers had a thickness of about 2 m each. Hence, the dimensions of each batch were ~5 m in length, ~5 m in width and either ~2 m or ~4 m in depth, depending on the targeted material to be excavated. Directly after excavation, each batch was pre-processed individually with a ballistic separator (Stadler model STT 6000) in two steps; first with screen paddles of 200 mm and subsequently with screen paddles of 90 mm in cascade arrangement. The fine fractions processed in this case study correspond to the underscreen fraction <90 mm obtained after the second ballistic separation step. Information about the coarse fractions (material ≥90 mm), as well as further details about the ballistic separation process have been reported by García López et al., 2019.

During the pre-processing of each batch representative single samples from the underscreen output fraction of the ballistic separator were taken, and composite samples were prepared from the single samples. This study focuses solely on the mechanical processing of the composite samples of batches 1 and 2, from which a total of 32 single samples (16 single samples for each batch) of 10 l were taken and 16 composite samples (8 composite samples for each batch) of 20 l were prepared using the quartering method, according to the German guideline for procedures for physical, chemical and biological testing in relation to the recovery/disposal of waste (LAGA PN 98).

Further information regarding the landfill site, excavation works, material pre-processing and sampling procedures are reported in Hernández Parrodi et al., 2019a. The results of all composite samples, material fractions and particle size ranges (i.e. material characterization, (optimal) water content and mechanical processing) presented herein are based on mass percentage (wt.%), for which an industrial platform scale (Kern DS 150K1, resolution of 1.0 g) and a precision balance (Kern KB 2400-2N, resolution of 0.01 g) were employed. Water and dry mass contents were determined according to the DIN EN 14346 (modified: drying at 75 °C ± 5 °C to avoid melting of certain plastics and material losses), while the drying processes were carried out in a Heraeus industrial drying oven.

2.2 Fine fractions

The material characterization of the fine fractions from the MSG landfill was performed by Hernández Parrodi et al., 2019a, who reported overall ranges for bulk density and water content of 720-1 000 kg/m^3 (median of 810 kg/m^3) and 25-30 wt.% (median of 27 wt.%), respectively. The data of the material composition of the fine fractions 90-10 mm in dry state from that study was reclassified in 3 particle size ranges (i.e. 90-31.5 mm, 31.5-10 mm and Fine fractions <10 mm) and 7 grouped material fractions (i.e. "Combustibles", "Inert", "Fe metals", "Non-Fe metals", "Others", "Agglomerated fines <10 mm" and "Mixed materials") in this study, in order to allow direct comparison with the results of the mechanical processing. The reclassification consisted in separating the grouped material fraction "Total metals" from the material characterization into the fractions "Fe metals" and "Non-Fe metals", as well as in joining the particle size ranges 90-63 mm and 63-31.5 mm to form a particle size range of 90-31.5 mm. This information is shown in Table 1.

Figures in Table 1 were calculated using the 25th, 50th (median) and 75th percentiles in order to depict the variation range of the amount of each grouped material fraction, which can be used as reference to evaluate the recovery of "Combustibles", "Inert", "Fe metals" and "Non-Fe metals" from the fine fractions of the MSG landfill in the tested mechanical processing. These figures show that median amounts of about 4.0 wt.% "Combustibles", 13.3 wt.% "Inert", 0.3 wt.% "Fe metals" and 0.2 wt.% "Non-Fe metals" could be recovered from particle size range 90-31.5 mm, while around 3.7 wt.% "Combustibles", 19.9 wt.% "Inert", 0.3 wt.% "Fe metals" and 0.1 wt.% "Non-Fe metals" could be obtained from particle size range 31.5-10 mm. Additionally, about half of the total amount of the fine fractions (median of 51.8 wt.%) can be expected to be <10 mm.

TABLE 1: Material composition of the fine fractions in dry state (modified from Hernández Parrodi et al., 2019a).

Particle size range/Grouped material fraction		Amount [wt.%]		
		25th percentile	Median	75th percentile
90-31.5 mm	Combustibles	0.9	4.0	9.9
	Inert	9.7	13.3	15.1
	Fe metals	0.2	0.3	0.7
	Non-Fe metals	0.0	0.2	0.5
	Others	0.0	0.2	1.9
	Agglomerated fines <10 mm	0.2	0.3	0.4
31.5-10 mm	Combustibles	1.3	3.7	9.6
	Inert	17.8	19.9	22.2
	Fe metals	0.2	0.3	0.5
	Non-Fe metals	0.1	0.1	0.2
	Others	0.4	0.6	1.1
	Agglomerated fines <10 mm	2.9	3.5	3.8
Fine fractions <10 mm	Mixed materials	37.8	51.8	55.6

Notes: Total amounts do not account for 100 wt.% due to the utilization of quantiles.

2.3 Particle size distribution and water content

A study on the particle size distribution of the fine fractions from batches 1 and 2 with different water contents was carried out in order to identify the optimal water content. The optimal water content is that with which the fine fractions are still able to be handled efficiently in a dry mechanical process without the need of complete drying. Theoretically, less resources (i.e. energy and time) would be needed to reach adequate mechanical processing in this way, while material losses and dust generation would be decreased significantly. Eight composite samples of batch 1 (n=4) and batch 2 (n=4) were used to determine the range of the particle size distribution with water contents of 10 wt.% and 20 wt.%, respectively. Initially all composite samples were dried completely according to the DIN EN 14346 (as described in Section 2.1) and, subsequently, the corresponding water contents were set following the procedure described in Section 2.4.1. Afterwards, the composite samples were sieved in a circular vibratory box sieve (Siebtechnik, 500 mm x 500 mm) with circular reticle sieves of 63 mm, 31.5 mm and 10.0 mm, followed by a sieving with a circular vibratory sieve tower (Siebtechnik, Ø 400 mm) with squared reticle sieves of 6.3 mm, 3.15 mm, 1.0 mm, 0.63 mm, 0.315 mm and 0.16 mm, according to the DIN EN 15415-1:2011. Finally, the obtained curves were compared to the particle size distribution ranges from both batches in raw (n=8) and dry (n=8) states from the material characterization (Hernández Parrodi et al., 2019a) in order to identify the optimal water content.

2.4 Mechanical processing

A specific process chain of mechanical equipment was selected to process the fine fractions according to the results of the material characterization and the defined strategies for WtM and WtE reported in Hernández Parrodi et al., 2019a. This arrangement was selected with the main objective of optimizing the recovery of certain fractions from the fine fractions; such as a fraction with high calorific value that could be used as an alternative fuel (e.g. RDF/Solid Recovered Fuel (SRF)), an inert fraction that could be used as substitute for construction aggregates (e.g. construction sand/gravel) and a soil-like fraction (i.e. fine fractions <4.5 mm) that could be used as substitute for soil in construction applications (e.g. dykes/embankments), as well as fractions composed of Fe and non-Fe metals that could be recycled. At the same time, the selected arrangement aims at reducing the amount of the fine fractions to be re-landfilled or stored until more adequate technologies are developed for its valorization or further utilization. To this end, a dry mechanical processing approach was chosen, since wet processing methods tend to be more elaborate and complex, and have been associated with higher capital and operational costs in the past (Bunge, 2012). Additionally, wet methods involve sending a certain share of impurities and contaminants to an aqueous medium, which must be treated at some point as well. Furthermore, in the context of (E)LFM most of the outputs of a wet processing approach will need a significant reduction in moisture before being suitable for WtM and WtE schemes.

Figure 1 presents an overview of the mechanical processing approach implemented in this study. The whole mechanical processing was investigated using composite samples of batches 1 and 2 in the optimal water content state (n=8) and in the dry state (n=8), in which 4 composite samples of each batch were processed in the optimal water content state and 4 composite samples in the dry state. Each composite sample was processed individually in order to study the variation between samples as well. Figure 1 shows two main material flows (black arrows): one for the composite samples in the optimal water content state and one for those in the dry state.

In order to avoid further alteration of the composite samples (e.g. moisture gain/loss, material loss, weathering and fractionation), the calibration of all processing equipment, except for the sensor-based sorter, was performed by means of artificial samples, which were composed of similar type of materials in new state (i.e. hard and soft plastics, paper, wood, glass, stones, metals and soil) and prepared in such a way that the main characteristics of the material (i.e. composition, density, particle size range and water content) were simulated. The sensor-based sorting equipment was calibrated with real representative pieces of each material type selected by hand, since the actual spectra of each material were needed for the calibration of the equipment.

Most of the materials with high calorific value (e.g. plastics, textiles, leather, paper and wood) were expected to be found in the light fractions and, hence, a fraction called "Combustibles", which is marked in purple in Figure 1, was generated with those materials to produce an alternative fuel, which might be suitable for thermal valorization. To this end, thermogravimetry has proven to be a promising method to determine the composition of such materials and study their decomposition in thermo-chemical conversion processes, such as incineration, pyrolysis and gasification, and, thus, can be helpful for selecting the most appropriate option to be employed (Burlakovs et al., 2019). Inert materials (e.g. bricks, concrete, stones, glass and ceramics) were anticipated in the heavy fractions and, thus, a fraction denominated "Inert", which is marked in grey in Figure 1, was generated with these fractions in order to produce a substitute for construction aggregates. In addition, seashells, which are not scarce in Belgian MSW, were sorted out of the "Inert" fraction by means of sensor-based sorting and were incorporated in the "Combustibles" fraction, since they have proven to act as an effective antichlor agent (Tameda et al., 2018) due to their high calcium carbonate content. Fe and non-Fe metals, which are

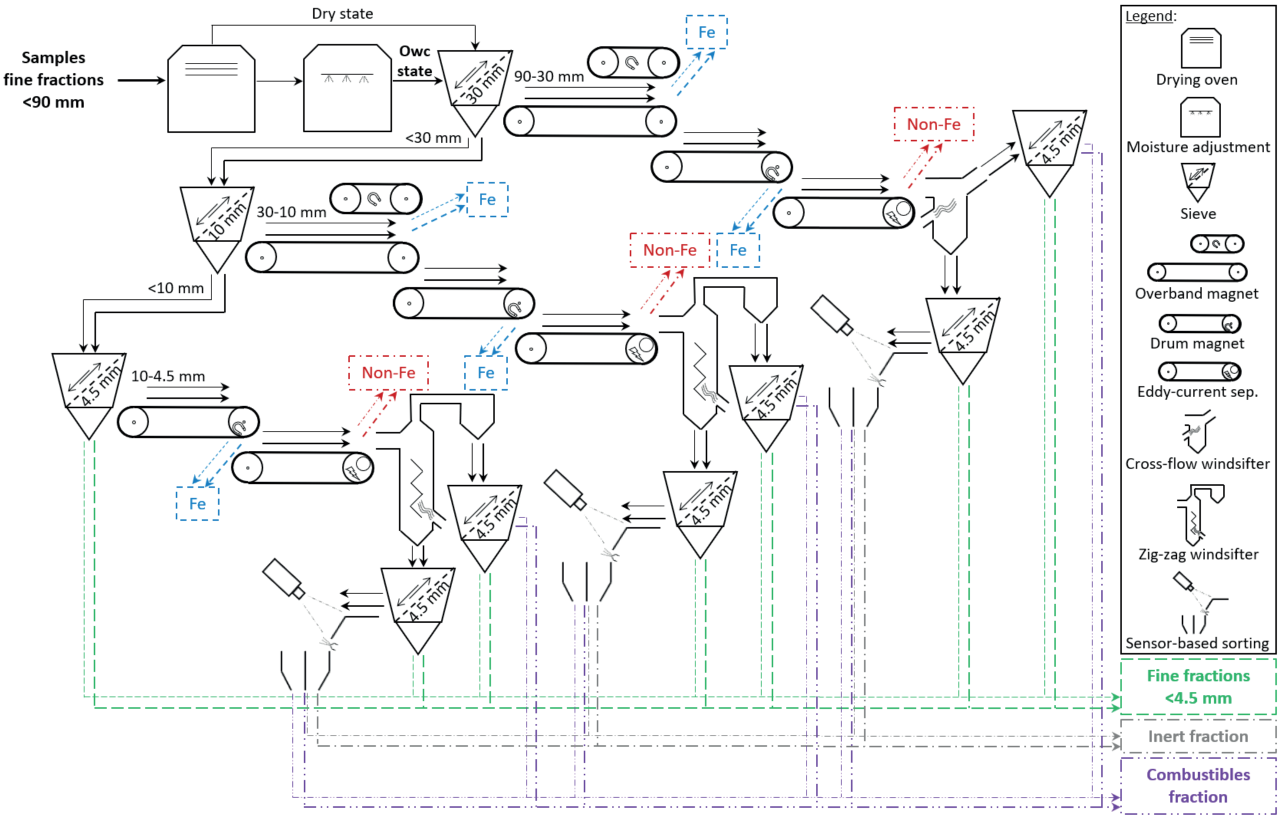

FIGURE 1: Mechanical processing flow chart of the fine fractions in the optimal water content (owc) and dry states.

respectively marked in blue and red in Figure 1, were also extracted from the fine fractions, since they can represent a substantial share of the revenues from LFM (Van Vossen & Prent, 2011; Winterstetter, Laner, Rechberger, & Fellner, 2015). The results on the quality assessment of the recovered non-Fe metals for recycling purposes are reported in Lucas et al., 2019. However, the recovery of ferrous metals from landfilled material is nowadays regarded as technically possible, since it has been successfully performed in previous LFM investigations (Van Vossen & Prent, 2011; Wagner & Raymond, 2015). Hence, the quality of the extracted ferrous metals was not investigated in the present case study.

Additionally, a fraction named “Fine fractions <4.5 mm”, which is marked in green in Figure 1, was created with the recovered surface defilements and agglomerates liberated by the coarser particle size ranges (i.e. 90-30 mm, 30-10 mm and 10-4.5 mm) along the mechanical processing, as well as with the underscreen fraction from the sieving step at 4.5 mm. The properties of the “Fine fractions <4.5 mm” will be studied in order to determine if a substitute for soil in construction applications could be produced with the whole or a certain amount of this fraction.

The mechanical processing until sieving steps at 4.5 mm was carried out at the technical facilities of the Department of Processing and Recycling (IAR) of the RWTH Aachen University, whereas the sensor-based sorting steps were performed at the technical laboratory of the Chair of Waste Processing Technology and Waste Management (AVAW) of the Montanuniversität Leoben. For explanatory purposes, the mechanical processing was organized in five stages: i) material conditioning, ii) particle size classification, iii) extraction of Fe and non-Fe metals, iv) separation of light and heavy fractions and v) quality improvement of light and heavy fractions. These stages are described in the following sections of this chapter.

2.4.1 Material conditioning

There are several industrial options for drying or reducing the water content of landfill-mined material, such as aeration pile, biodrying and drum furnace, among others. Each of those options has its own advantages, limitations and cost implications towards (E)LFM, which can be very relevant and, thus, must be carefully assessed beforehand. However, the drying process is not the main focus of the present study and, therefore, it is not discussed further on.

In order to set the target water contents (i.e. optimal water content state and dry state) for the 2 scenarios of the mechanical processing, the composite samples of both batches were completely dried in the industrial drying oven according to the DIN EN 14346 (as described in Section 2.1). Subsequently, water was added to half of the composite samples (n=4) of each batch until the optimal water content was reached. For this, tap water was gradually and uniformly sprinkled in layers of about 3 cm with a manual pressurized water sprayer (GLORIA prima 3 l – 3 bar) in a 90 l container. The material was thoroughly mixed and was left to rest for 24 h, in such a way that the water addition was evenly distributed throughout the whole sample. The remaining half of the composite samples (n=4) of each batch was kept in dry state.

After setting the target water contents, the mechanical processing was conducted separately for the two groups of samples: i) composite samples (n=8) in the optimal water content state and ii) composite samples (n=8) in the dry state. Both groups of samples included composite samples of each batch (n=4) and, from this point on, all composite samples were processed identically.

2.4.2 Particle size classification

Directly after the adjustment of water content the composite samples were classified into the following 4 particle size ranges:

- 90-30 mm
- 30-10 mm
- 10-4.5 mm
- <4.5 mm

The previous particle size ranges were selected according to the results of the material characterization reported in Hernández Parrodi et al., 2019a, targeting a minimum amount of sieving steps and a maximum amount of recoverable material per particle size range. This particle size classification was done using two different types of sieves for waste materials.

The first sieving step was performed with a circular motion vibrating sieve for waste materials (iFE waste screen for waste treatment and recycling) with 30 mm squared sieve panels (Figure 2a). This type of sieve was used due to its vibrating circular motion operating principle, robustness and cascade arrangement of the screening panels, which make it adequate for sieving heterogeneous humid waste mixtures with minimum clogging. This equipment had a total sieving length of 2.0 m and width of 0.8 m and was operated with a fixed inclination of 15°. As it is shown in Figure 2a, the sieve was feed by means of a 5.0 m long conveyor belt with a slope of 42°. The median throughput was ca. 13 kg (1 composite sample) per run, for which around 1 minute processing time was needed in the optimal water content state. In the dry state ca. 11 kg (median) was processed using the same duration.

The second and third sieving steps were done with a flip-flow type of sieve (Hein Lehmann LIWELL® screening machine) with 10 mm and 4.5 mm squared screen mats, respectively (Figure 2b). A flip-flow sieve was selected as it can cope with materials difficult to sieve due to their small grain size, moist and/or sticky nature, which is the case for the fine fractions from (E)LFM. This equipment uses flexible screen mats to apply a trampoline-like movement that prevents the sieve from clogging, while breaking apart material agglomerates and sieving the input material in a uniform and continuous manner. The sieve had total functional length and width of about 3.0 m and 0.5 m, respectively, and was operated with an inclination of 25°. In the second sieving step ca. 10 kg (median) of material was sieved at 10 mm for 1 minute per composite sample in the optimal water content state, whereas ca. 8 kg (median) was sieved in the dry state. In the third sieving step

FIGURE 2: a) Circular motion vibrating and b) flip-flow sieves.

ca. 7 kg (median) of material was sieved at 4.5 mm for 1 minute in the optimal water content state and ca. 6 kg (median) in the dry state.

2.4.3 Extraction of Fe and non-Fe metals

Fe and non-Fe metals were removed by magnetic and eddy-current separators. Fe metals were extracted using an overband magnet (Figure 3a) followed by a drum magnet (Figure 3b), in a cascade arrangement, in particle size ranges 90-30 mm and 30-10 mm, while they were removed employing only the drum magnet in the particle size range 10-4.5 mm. The overband magnet was used to extract the largest particles of the Fe metals fraction with high quality (low content of impurities), as the magnet was located above the throughput flow and pulled Fe metals out of the stream. In turn, the drum magnet was located below the throughput flow and pulled Fe metals out of the stream downwards. Thus, the drum magnet was used to remove the remainder of Fe metals, which ranged from Fe metal pieces attached to other materials to the smallest Fe particles (incl. iron filings and iron oxides) present in the throughput, and which normally have a poor quality. Additionally, the drum magnet was employed to protect subsequent processing equipment, i.e. eddy-current separator, since the presence of Fe metals can lead to overheating and malfunction of such equipment.

The employed overband magnet was a permanent Steinert suspension magnet (750 mm long and 100 mm wide) placed transversely to the throughput flow. A spacing of 180 mm was used for the particle size range 90-30 mm with respect to the conveyor belt transporting the material, while one of 60 mm was utilized for the particle size range 30-10 mm in both the optimal water content and dry states. The overband magnet was operated with a constant speed of about 1.5 m/s and the conveyor belt was set to a constant speed of around 1.0 m/s in both states. As for the drum magnet, a permanent Steinert drum magnetic separator (300 mm diameter and 500 mm long) was utilized, which was operated in both states at 35 rpm and fed by a vibratory conveyor at an approximate rate of 0.5 kg/minute.

Non-Fe metals were extracted by means of a permanent Steinert eccentric eddy-current separator (500 mm diameter and 800 mm long) operated at 3 000 rpm with an eccentricity of 30° for the particle size range 90-30 mm,

FIGURE 3: a) Overband magnetic, b) drum magnetic and c) Eddy-current separators.

36° for 30-10 mm and 42° for 10-4.5 mm in both states (Figure 3c). This machine was equipped with a vibratory conveyor and a conveyor belt, with which the material was driven over the eddy-current magnetic wheel at a speed of about 1.5 m/s for all samples.

2.4.4 Separation of light and heavy fractions

Windsifting was used to split light from heavy materials. This density separation method uses material properties, such as density and shape to separate the throughput by means of a stream of air, which carries light materials to a different recipient.

A cross-flow windsifter (cross-flow air classifier, self-made by the IAR) was employed to process the particle size range 90-30 mm (Figure 4a). This equipment blows a bottom up stream of air across the throughput flow in a transversal way and light materials are transported by the air stream along a pipe to a container, while heavy materials fall down at the air stream contact area and are collected in a separate container. This equipment was utilized since it is relatively robust and can handle particle sizes up to around 200 mm. During the operation of the cross-flow windsifter, an airflow volume flow of about 7 000 m^3/h was employed and the input material was delivered at a rate of around 1 kg/minute in both states. The fixed angle with which the air stream was injected was 45° with respect to the horizontal plane.

For the processing of the particle size ranges 30-10 mm and 10-4.5 mm a zig-zag windsifter (Graf zig-zag air classifier, custom made for the IAR) was used (Figure 4b), as it can separate small grain-sized materials with high precision. In this equipment the input material is delivered by an airtight vibratory conveyor into a horizontal zig-zag shaped channel, where an air stream is blown from bottom to top. The zig-zag shaped channel creates a combination of cross- and counter-flow air streams along multiple steps that transport light particles into an aerocyclone and subsequently to a separate recipient. The heavy fraction slides down over the zig-zag shaped channel and is collected in a container. The zig-zag windsifter was operated with an airflow speed range of 7.5-8.5 m/s for the particle size 30-10 mm, whereas 6.5-7.5 m/s was used for 10-4.5 mm in both states. The zig-zag shaped channel was around 1.2 m long and the input material was fed at a rate of about 0.5 kg/minute for the particle size range 30-10 mm and of 0.3 kg/minute for 10-4.5 mm in both states.

FIGURE 4: a) Cross-flow and b) zig-zag windsifters.

2.4.5 Enrichment and quality improvement of light and heavy fractions

Surface defilements, agglomerates and fine particles from material weathering are loosened and released along mechanical processing. These fine materials can be removed in order to improve the quality of the output fractions. Moreover, certain combustible materials with high densities might still be found in the heavy fractions after density separation. Such materials can be removed from the heavy fraction by means of sensor-based sorting, so that the quality of the heavy fractions is improved and the amount of materials with high calorific value can be valorized together with the "Combustibles" fraction.

Light and heavy fractions from the cross-flow and zig-zag windsifters were sieved further in order to remove released fine particles along the whole mechanical processing. This sieving was performed with a circular vibratory sieve tower (Siebtechnik, Ø 400 mm) with a squared reticle sieve of 4.5 mm during 1 minute in both states, since the amount of light and heavy fractions obtained from the density separation steps did not allow the employment of a larger scale equipment. Additionally, this last sieving step served the purpose of preconditioning the heavy fraction for the sensor-based sorting step, in which the presence of dust and fine particles interferes with the correct recognition and classification of the input material. The reduction of impurities in the light fraction might lead to reduce the ash content and, thus, to raise the calorific value, as well as to decrease the amount of certain contaminants, such as heavy metals and organic pollutants. Moreover, the underscreen fraction below 4.5 mm from the light and heavy fractions could be jointly valorized or processed further with the fraction "Fine fractions <4.5 mm" in this manner.

Near infrared (NIR) was employed by the sensor-based sorter to measure the wavelength with which a certain material reflects infrared radiation. Such measurements are then used to compute the spectrum variation for each material, which is either left in the material stream or sorted out, according to the desired set up of the equipment. The sorting is done by means of a pulse of pressurized air released through a nozzle, which shoots the particles to be sorted out, sending them to a separate container. To this end, a pilot scale sensor-based sorter manufactured by binder + co with a hyperspectral imaging (HIS) chute was utilized (Figure 5), which was equipped with a vibratory conveyor.

FIGURE 5: Sensor-based sorting equipment.

In this last processing step of the heavy fractions from the windsifting steps, the material was fed to the sensor recognition area at a rate of about 1 kg/minute, 0.5 kg/minute and 0.3 kg/minute for the particle size ranges 90-30 mm, 30-10 mm and 10-4.5 mm, respectively, in both states. The pressurized air was set to different pressures as well, which were 3 bar for 90-30 mm, 2 bar for 30-10 mm and 1.5 bar for 10-4.5 mm in both states. Further details about this processing step are reported in Küppers, Hernández Parrodi, García López, Pomberger, & Vollprecht, 2019.

3. RESULTS AND DISCUSSION

3.1 Optimal water content

Particle size distribution curves were calculated for the composite samples of batch 1 and batch 2 with median water contents of 0 wt.% (dry state), 10 wt.%, 20 wt.% and 27 wt.% (raw state), and analogously as for the material composition (Section 2.2), quantiles (25th, 50th and 75th percentiles) were used to determine the variation range in each water content. The particle size distribution curves (solid lines) for each water content, as well as their variation ranges (dash and dash-dot lines), are plotted in Figure 6.

The particle size distribution curves in Figure 6 show a slight alteration of the particle size distribution with water contents of 10 wt.% and 20 wt.% above 3 mm. This suggests that the structure of the material might most likely have experienced fragmentation, material losses and a sort of cleaning effect due to complete drying, remixing, re-moisturization and a second particle size classification (i.e. sieving), since the same composite samples used to determine the particle size distribution in raw state of both batches were used for the adjusted water contents. This was the case because there were no additional virgin samples from the fine fractions available for this purpose. Nevertheless, taking into account that relevant amounts of grouped material fractions other than "Agglomerated fines <10 mm" (i.e. "Combustibles", "Inert", "Fe metals", "Non-Fe metals" and "Others") were not identified below a particle size of 3.15 mm during the material characterization of the fine fractions (Hernández Parrodi et al., 2019a), the sorting of the fine fractions into "Combustibles + Others", "Inert", "Fe metals" and "Non-Fe metals" would only make sense above 3 mm. Thus, given that the curve for 10 wt.% water content could be expected to be very close to the one in dry state, it was concluded that a reduction of the original water content (median of 27 wt.%) to around 15 wt.% would suffice to allow an adequate mechanical processing of the fine fractions above 3 mm. The latter, assuming that the additional amount of surface defilements in comparison to dry state, which was visually determined as not quantitatively relevant, would not interfere significantly with the efficiency and effectiveness of the sensor-based sorting steps of the mechanical processing, nor to meet the quality standards of the targeted outputs (i.e. RDF, substitutes for construction aggregates and soil in construction applications, and ferrous and non-ferrous metals). Nonetheless, a further reduction of the water content might be required for adequate particle size classification below 3 mm; especially below 0.6 mm, where the needed reduction appears to be below 10 wt.%.

Therefore, in order to assess the potential for material and energy recovery from the fine fractions of the MSG landfill through the selected dry mechanical processing approach, 2 scenarios with different water contents were studied and compared. These scenarios correspond to the above determined optimal water content state of 15 wt.% and the dry state.

3.2 General mass balance

In order to obtain a full overview of the mass distribution in the tested mechanical processing of the fine fractions, the outputs of the whole mechanical processing were classified into 6 categories, namely "Fine fractions <4.5 mm", "Inert", "Combustibles", "Fe metals", "Non-Fe metals" and, depending on the state, either "Material & water losses" for the optimal water content state or "Material losses" for the dry state. The output "Fine fractions <4.5 mm" in this case study corresponds to the material that was generated by a sieving step at 4.5 mm along the mechanical proces-

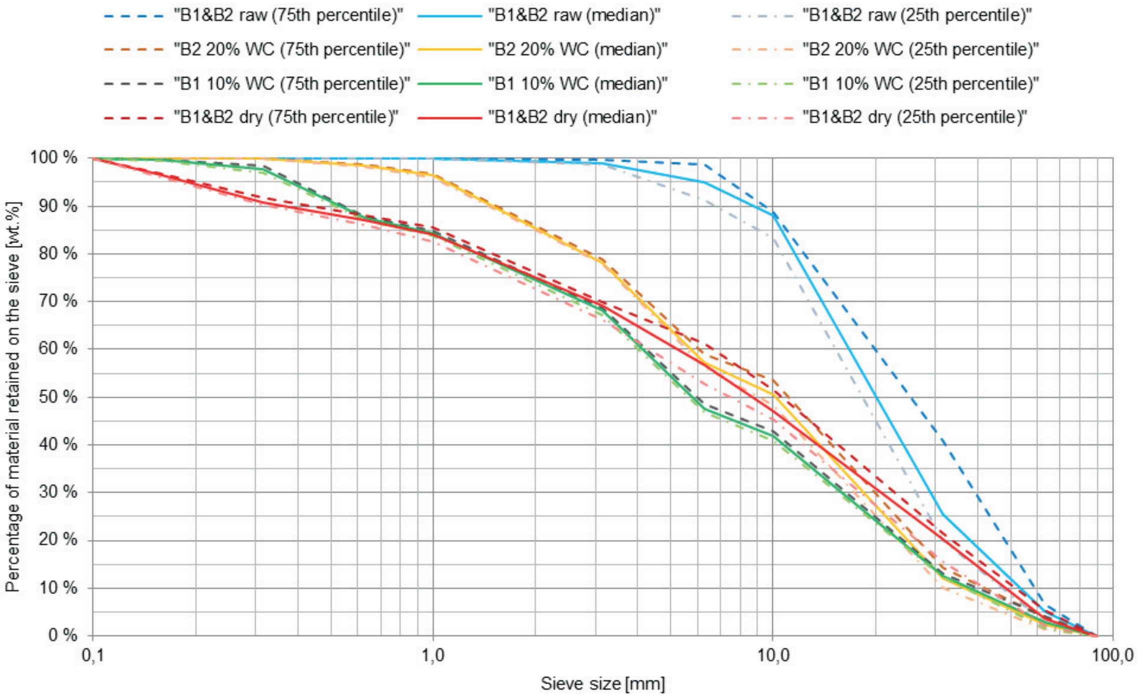

FIGURE 6: Particle size distribution of the fine fractions with different water contents.

sing, and it is referred to as "Soil-like material" concerning its apparent material composition. It is relevant to clarify that, as stated in Hernández Parrodi, Höllen, & Pomberger, 2018b, the term "Soil-like material" does not intend to rigorously classify this material as soil, but instead employs it for reasons of appearance, as well as because it is a commonly used term in the field. The amount of each category for each composite sample was determined for each state and the median was calculated (n=8). This information is displayed for each category and state in form of Sankey diagrams in Figure 7.

As shown in Figure 7, both the optimal water content state and the dry state presented the same tendency in terms of the amounts obtained from each output of the mechanical processing, in which most of the fine fractions corresponded to the "Fine fractions <4.5 mm" output, with amounts of 42.9 wt.% and 42.7 wt.%, respectively. That output was followed by "Inert", with amounts of 35.5 wt.% in the optimal water content state and 37.2 wt.% in the dry state. "Combustibles" output followed "Inert" with the respective amounts of 12.5 wt.% and 9.0 wt.% in the optimal water content and dry states. Subsequently, "Material & water losses" in the optimal water content state were slightly lower than "Material losses" in the dry state, with amounts of 7.6 wt.% and 7.9 wt.%, respectively. This may be explained by the fact that the presence of water increased the weight of certain materials to some extent and promoted the formation of surface defilements and agglomerates of fine particle sized material (<1 mm), which in turn decreased the loss of light and small particle sized materials (e.g. plastic foils and dust). However, it should be said that the material in the dry state might also have been influenced to a certain extent by the presence of water due to absorption/adsorption of humidity from the environment, which was not monitored throughout the whole mechanical processing nor taken into account in the mass balance of this state. Hence, the mass increase due to the influence of humidity from the environment might have compensated for a certain amount of material losses in the dry state, as well as decreased losses in the form of dust. Therefore, material losses in a strictly dry state might be higher than those reported in the present study. As for the amounts of "Fe metals" and "Non-Fe metals" outputs, a lower amount of "Fe metals" (0.9 wt.%) was obtained in the optimal water content state with respect to the dry state (1.4 wt.%), whilst the amount of "Non-Fe metals" obtained in the optimal water content state (0.4 wt.%) was slightly larger than in the dry state (0.3 wt.%). Discrepancies regarding the amounts between outputs "Fine fractions <4.5 mm", "Inert", "Combustibles", "Fe metals" and "Non-Fe metals" in the optimal water content and dry states are addressed in the following section.

3.3 Mass balance of grouped material fractions per particle size range

Regarding the different materials recovered from the fine fractions and, analogously to the results of the material characterization presented in Section 3.1, a mass balance of the obtained materials according to particle size range was performed using quantiles. The resulting information was organized according to the following grouped material fractions: "Combustibles", "Inert", "Fe metals", "Non-Fe metals" and "Fine fractions <4.5 mm (Soil-like material)", which are in accordance with the categories used to classify the outputs of the mechanical processing in the previous section (Section 3.2) and the particle size ranges generated along the mechanical processing (i.e. 90-30 mm, 30-10 mm and 10-4.5 mm). These grouped ma-

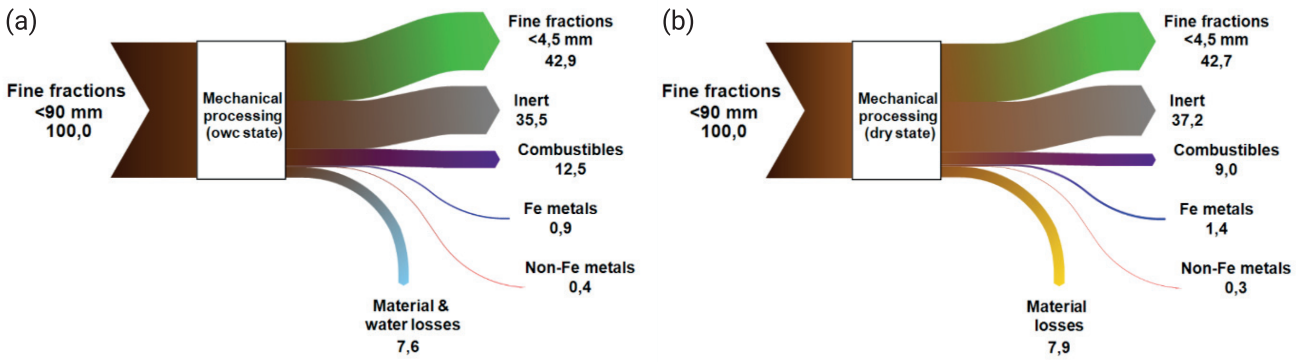

FIGURE 7: General mass balance of the mechanical processing in the a) optimal water content (owc) and b) dry states [figures in wt.%].

terial fractions are also in agreement with those of the material characterization presented in Table 1, except for the fraction "Fine fractions <4.5 mm (Soil-like material)", which has a particle size <4.5 mm and, hence, corresponds partially to fraction "Fine fractions <10 mm (Mixed materials)" and fraction "Others" of the material characterization, from which most part ended up in the fraction "Combustibles" of the mechanical processing due to its characteristics. Unlike material characterization, which was performed by hand down to a particle size of 10 mm, the mechanical processing was implemented down to 4.5 mm, since small amounts of recoverable materials were still visually identified below 10 mm and above 3.15 mm in the material characterization (Hernández Parrodi et al., 2019a). Thus, most of the fraction "Fine fractions <10 mm (Mixed materials)" is composed of the "Fine fractions <4.5 mm (Soil-like material)" fraction, whereas the remainder is expected to be distributed among the rest of the grouped material fractions (i.e. "Combustibles", "Inert", "Fe metals" and "Non-Fe metals") in the particle size range 10-4.5 mm of the mechanical processing.

The recovered amounts of each grouped material fraction according to particle size range for each state (i.e. the optimal water content and dry states) of the mechanical processing are summarized in Table 2, in which, in contrast to the rest of the figures in this article, two decimal figures were employed in order to depict the low amounts of non-Fe metals recovered from the particle size range 10-4.5 mm.

As is the case for the general mass balance discussed in Section 3.2, figures in Table 2 show a clear common trend with respect to the amount of each grouped material

TABLE 2: Amounts of grouped material fractions per particle size range from mechanical processing.

Particle size range / Grouped material fraction		Amount [wt.%]					
		15 wt.% water content			Dry state		
		25th percentile	Median	75th percentile	25th percentile	Median	75th percentile
90-30 mm	Combustibles	3.46	4.64	5.33	3.37	4.13	4.66
	Inert	13.57	15.26	16.87	15.06	15.47	16.10
	Fe metals	0.20	0.32	0.44	0.46	0.59	1.03
	Non-Fe metals	0.15	0.21	0.27	0.12	0.24	0.34
	Soil-like material	0.88	1.15	1.26	0.91	1.08	1.14
30-10 mm	Combustibles	4.57	4.96	6.72	2.34	2.67	3.16
	Inert	11.93	15.60	17.17	12.51	12.97	14.23
	Fe metals	0.26	0.46	0.55	0.27	0.38	0.55
	Non-Fe metals	0.11	0.15	0.15	0.05	0.07	0.08
	Soil-like material	0.79	0.81	0.87	1.00	1.28	1.37
10-4.5 mm	Combustibles	2.4	2.51	2.71	1.82	1.95	2.27
	Inert	5.84	6.31	6.83	6.06	8.06	9.90
	Fe metals	0.15	0.17	0.17	0.24	0.27	0.29
	Non-Fe metals	0.02	0.02	0.03	0.02	0.03	0.03
	Soil-like material	1.26	1.30	1.46	2.41	2.71	3.24
Fine fractions <4.5 mm	Soil-like material	36.88	39.54	40.27	36.90	37.50	39.12

Notes: Total amounts do not account for 100 wt.% due to losses of material and water (if the case) along mechanical processing and the utilization of quantiles.

fraction in particle size ranges 90-30 mm (in both states), 30-10 mm (in both states) and 10-4.5 mm (only in the optimal water content state), in which most of the material corresponded to the "Inert" fraction, followed by fractions "Combustibles", "Soil-like material", "Fe metals" and "Non-ferrous metals". This information shows that the trend presented by the fine fractions at a general level (particle size range 90-4.5 mm) was also valid at a more specific level (particle size ranges 90-30 mm, 30-10 mm and 10-4.5 mm). Nevertheless, this was the case only to a certain extent, since the same tendency was not identified in the particle size range 10-4.5 mm in the dry state, in which most of the material was allocated to the fraction "Inert", but, in contrast, the latter was followed by fraction "Soil-like material" instead of by fraction "Combustibles". This may be the case because, in general, fractions presented a lower amount of surface defilements in the dry state, which in the case of "Combustibles" in a particle size range of 10-4.5 mm might represent a significant loss in terms of mass. However, fractions "Fe metals" and "Non-Fe metals" in the particle size range 10-4.5 mm maintained the same trend as particle size ranges 90-30 mm and 30-10 mm.

In the optimal water content state, the particle size ranges 90-30 mm and 30-10 mm presented similar total amounts of material, with 21.6 wt.% and 22.0 wt.%, respectively; whereas the particle size range 10-4.5 mm accounted for 10.3 wt.%. In the dry state, most of the material was present in the particle size range 90-30 mm with an amount of 21.5 wt.%, followed by the particle size range 30-10 mm with 17.4 wt.% and by 10-4.5 mm with 13.0 wt.%. These figures show that the total amount of material in the dry state tended to decrease according to particle size in the particle size ranges between 90 mm and 4.5 mm. Additionally, the presence of water affected the amount of the particle size range 30-10 mm the most, which altered such trend in the optimal water content. Nonetheless, the presence of water also affected the amount of material in the particle size ranges 90-30 mm and 10-4.5 mm, although to a lesser extent; the 90-30 mm range was the least affected.

As for the total amounts of the grouped material fractions according to particle size range, results show that most of fractions "Combustibles", "Inert", "Fe metals" and "Non-Fe metals" was extracted from particle size ranges 90-30 mm and 30-10 mm in both states. Furthermore, the particle size range 30-10 mm was mostly affected by the presence of water, as the difference between the amount obtained in the dry state and the one obtained in the optimal water content state was the greatest in that particle size range. Notwithstanding, the particle size range 10-4.5 mm could be a relevant source of "Inert" fraction and could also be used to obtain an additional amount of "Combustibles". The amounts of "Soil-like material" increased as the particle size decreased from 90 mm to 4.5 mm in the dry state, whilst in the optimal water content state most of it was obtained in the particle size range 10-4.5 mm, followed by particle size ranges 90-30 mm and 30-10 mm. However, the fraction "Soil-like material" presented fair variations, in general, between the optimal water content and dry states, from which the highest corresponded to the particle size range 10-4.5 mm, followed by 30-10 mm. The grouped material fraction that showed a greater variation due to the presence of water was "Non-Fe metals" in the particle size range 30-10 mm, which showed a significant decrease in terms of amount in the dry state. In turn, fractions "Soil-like material" and "Ferrous metals" presented a significant increase in the dry state with respect to the optimal water content state. These variations are also likely due to the greater amount of surface defilements and agglomerates in the optimal water content state, which can affect the efficiency of separation processes and affect the mass of certain materials.

The previous information shows that the presence of water affected material types and particle sizes in similar and different ways at the same time, since it can increase the mass of a certain material by absorption/adsorption and/or the presence of surface defilements. This may alter the characteristics of that material, which might play a crucial role in a certain processing step (e.g. density separation and sensor-based sorting). Simultaneously, the presence of water can promote the formation of agglomerates that affect the particle size distribution of the fine fractions, which might also play an important role in mechanical processing steps (e.g. sieving and metals separation). In addition, dust generation and material losses were also affected by the presence of water, which presented lower amounts in the optimal water content state.

Comparing the amounts obtained from each grouped material fraction of the mechanical processing in particle sizes 90-30 mm and 30-10 mm in the dry state with those of the material characterization in particle sizes 90-31.5 mm and 31.5-10 mm in Table 1 shows that there were slight deviations among the amounts of both. This might mainly be attributed to the fact that the amounts of the material characterization were the result of the manual sorting of all four batches excavated at the MSG landfill, while those of the mechanical processing were the result of processing batch 1 and batch 2. However, such deviations are minor and, thus, it can be said that the amounts of each grouped material fraction obtained in the mechanical processing are in agreement with the expected quantities.

In order to summarize and evaluate the total obtained amount of each grouped material fraction from the fine fractions by means of the tested mechanical processing in the optimal water content and dry states, the amounts from particle size ranges 90-30 mm, 30-10 mm and 10-4.5 mm were accumulated in a single particle size range (i.e. 90-4.5 mm), while the amounts of "Soil-like material" from those particle size ranges were congregated in the grouped material fraction "Fine fractions <4.5 mm (Soil-like material)". This information is displayed in Table 3.

In the optimal water content state, total amounts of 40.0-43.6 wt.% "Soil-like material", 34.1-39.1 wt.% "Inert", 11.8-12.9 wt.% "Combustibles", 0.6-1.2 wt.% "Fe metals" and 0.2-0.5 wt.% "Non-Fe metals" were obtained. In turn, total amounts of 41.9-43.9 wt.% "Soil-like material", 35.9-39.0 wt.% "Inert", 7.4-10.0 wt.% "Combustibles", 1.2-1.8 wt.% "Fe metals" and 0.2-0.4 wt.% "Non-Fe metals" were obtained in the dry state.

Generally, it can be concluded that the higher recovered amounts of "Combustibles" and "Non-Fe metals" in the

TABLE 3: Total amounts of grouped material fractions from mechanical processing.

Particle size range / Grouped material fraction		Amount [wt.%]					
		15 wt.% water content			Dry state		
		25th percentile	Median	75th percentile	25th percentile	Median	75th percentile
90-4.5 mm	Combustibles	11.8	12.5	12.9	7.4	9.0	10.0
	Inert	34.1	35.5	39.1	35.9	37.2	39.0
	Fe metals	0.6	0.9	1.2	1.2	1.4	1.8
	Non-Fe metals	0.2	0.4	0.5	0.2	0.3	0.4
Fine fractions <4.5 mm	Soil-like material	40.0	42.9	43.6	41.9	42.7	43.9

Notes: Total amounts do not account for 100 wt.% due to losses of material and water (if the case) along mechanical processing and the utilization of quantiles.

optimal water content state with respect to the dry state can be attributed to the absorption/adsorption of water by some of the materials present in those fractions, such as textiles and leather in the “Combustibles” fraction and “Fine fractions <4.5 mm (Soil-like material)” in the form of surface defilements and impurities in both fractions, rather than to a better performance of the mechanical processing in the optimal water content state. Controversially, almost equal amounts of “Fine fractions <4.5 mm (Soil-like material)” were obtained in both states, while a lower amount of that fraction would have been expected in the optimal water content. This was likely the case because most of the water was absorbed/adsorbed by the “Fine fractions <4.5 mm (Soil-like material)” fraction, which compensated for the amount of the latter lost to the “Combustibles”, “Inert”, “Fe metals” and “Non-Fe metals” fractions in the optimal water content state. In addition, a larger amount of “Inert” was obtained in the dry state than in the optimal water content state, which may also be explained by the influence of water in all fractions in the optimal water content state. Moreover, results suggest that the recovery of “Fe metals” can be increased by processing the material in the dry state, while the quality of the recovered “Non-Fe metals” can be improved in the same manner.

Furthermore, it can be said that the results from the mechanical processing in both states are in agreement with the total amounts of the material characterization of the fine fractions obtained by Hernández Parrodi et al., 2019a, in dry state: in that study amounts in the ranges of 37.8-55.6 wt.% “Fine fractions <10 mm (Mixed materials)”, 31.1-35.4 wt.% “Inert”, 2.1-19.7 wt.% “Combustibles”, 3.3-4.2 wt.% “Agglomerated fines <10 mm”, 0.6-3.4 wt.% “Others” and 0.6-1.8 wt.% “Total metals” were reported. One should take into account the following considerations: i) the fine fractions were segregated to a greater extent in the mechanical processing than in the material characterization (i.e. 4.5 mm vs. 10 mm, respectively), ii) most of the fraction “Others” of the material characterization is expected to be distributed among the fractions “Combustibles” and “Inert” of the mechanical processing, iii) most of the fraction “Agglomerated fines <10 mm” of the material characterization is expected to be in the fraction “Inert” of the mechanical processing, iv) material losses were greater in the mechanical processing than in the material characterization (i.e. ca. 8 wt.% vs. <2 wt.%, respectively), v) amounts of surface defilements and agglomerates were most likely affected by the fact that the same composite samples were used firstly for the material characterization and secondly for the mechanical processing, and vi) the results of the material characterization take into account the 4 excavated batches at the MSG landfill, while the material processing was performed with 2 batches. Moreover, it is relevant to highlight that an additional total amount of over 10 wt.%, distributed among grouped material fractions “Combustibles”, “Inert”, “Fe metals” and “Non-Fe metals”, could be obtained in both states by processing the fine fractions down to a particle size of 4.5 mm.

The results of the mechanical processing in the optimal water content state (water content of ca. 15 wt.%) were not compared to those of the material characterization in raw state (water content of ca. 27 wt.%) due to significant differences in water content. Furthermore, the optimal water content state is considered as an alternative to process the fine fractions in dry state with lower energy demand, material loss and dust emissions. Therefore, the mechanical processing tested in this study can be regarded as a successful approach to separate the fine fractions into sub-fractions in an effective and efficient manner, which facilitate WtM and WtE schemes. Nevertheless, this is to be verified by means of laboratory analysis as a next step.

3.4 Physical appearance of output fractions

In order to document and discuss the physical appearance of all grouped material fractions obtained from the tested mechanical processing, photographs of each output fraction in both the optimal water content and dry states were taken on a grid of 1 cm per 1 cm. Figure 8 displays pictures of the grouped material fractions “Combustibles”, “Inert”, “Fe metals” and “Non-Fe metals” obtained in the optimal water content state, while images of the same fractions obtained in the dry state are shown in Figure 9.

The comparison of the images in Figure 8 to those in Figure 9 shows that the recovered grouped material fractions “Combustibles”, “Inert”, “Fe metals” and “Non-Fe metals” presented a greater amount of surface defilements and agglomerates (i.e. impurities), both mainly composed of fraction “Fine fractions <4.5 mm (Soil-like material)”, in the optimal water content state than in the dry state. This could be remediated by the implementation of one or se-

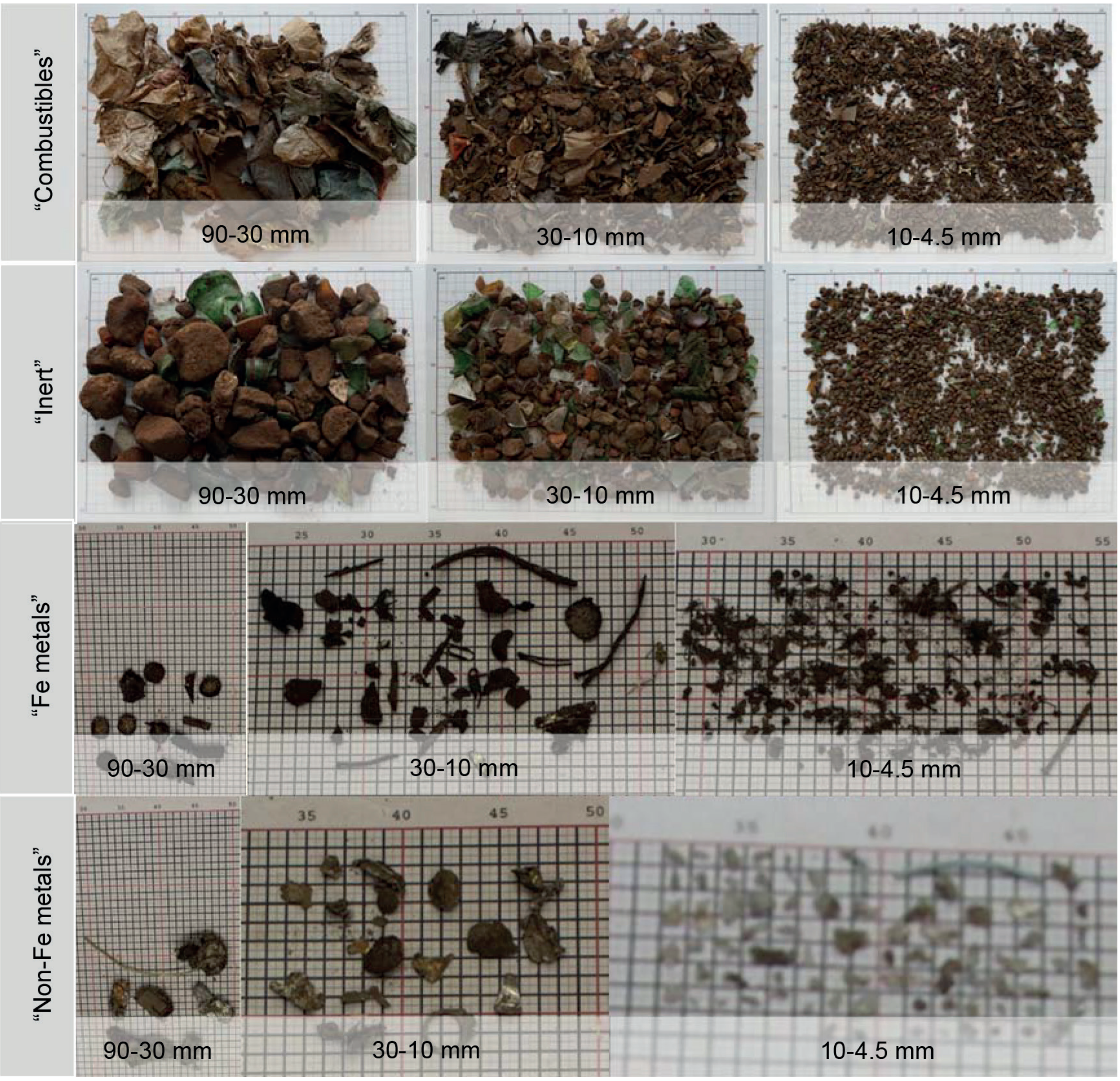

FIGURE 8: Grouped material fractions recovered in the optimal water content state.

veral washing steps, which could significantly reduce the amount of impurities (Tameda et al., 2018) in those fractions. However, the effectiveness of the mechanical processing in terms of its capability to separate the material throughput into the different grouped material fractions did not seem to be greatly affected, since there was no significant discrepancy of materials present in an incorrect grouped material fraction between both the optimal water content state and the dry state.

Regarding the physical appearance of fraction "Fine fraction <4.5 mm (Soil-like material)" in the optimal water content and dry states, Figure 10 shows that its visual characteristics did not differ significantly between both states. Nonetheless, a greater amount of agglomerated material <1 mm could be expected in the optimal water content state and, therefore, a reduction of the water content would be necessary for an adequate further dry mechanical processing of this fraction.

It is important to reiterate that laboratory analysis of the fractions "Combustibles", "Inert" and "Fine fractions <4.5 mm (Soil-like material)" are to follow the present study, in order to determine quantitatively if the applicable specifications for the foreseen purposes have been met by either one or both states, and therefore it cannot be yet assured, that the obtained outputs can be subject to valorization schemes of WtM and WtE.

4. CONCLUSIONS

In this study total amounts of 40.0-43.6 wt.% "Fine fractions <4.5 mm (Soil-like material)", 34.1-39.1 wt.% "Inert", 11.8-12.9 wt.% "Combustibles", 0.6-1.2 wt.% "Fe metals"

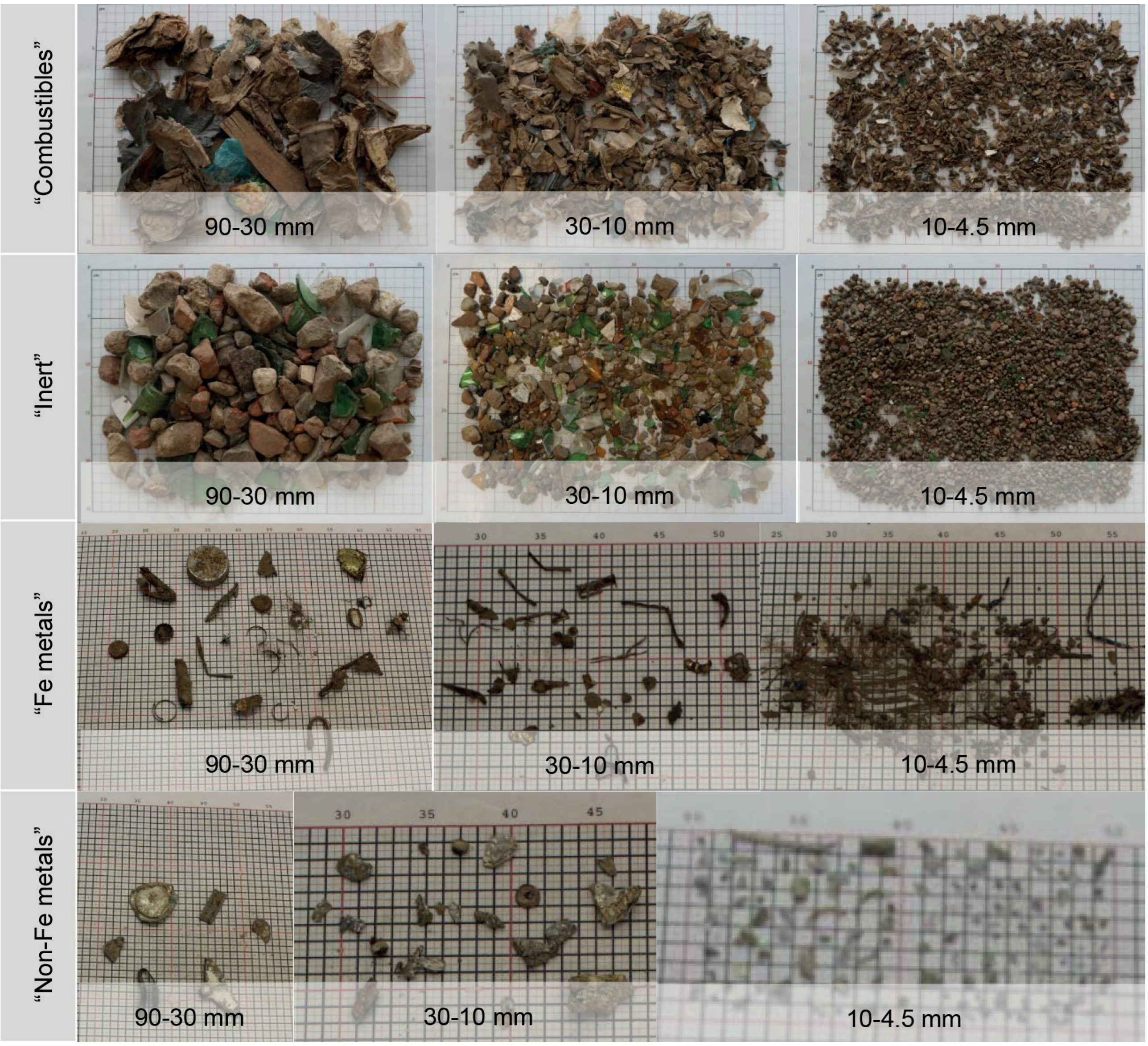

FIGURE 9: Grouped material fractions recovered in the dry state.

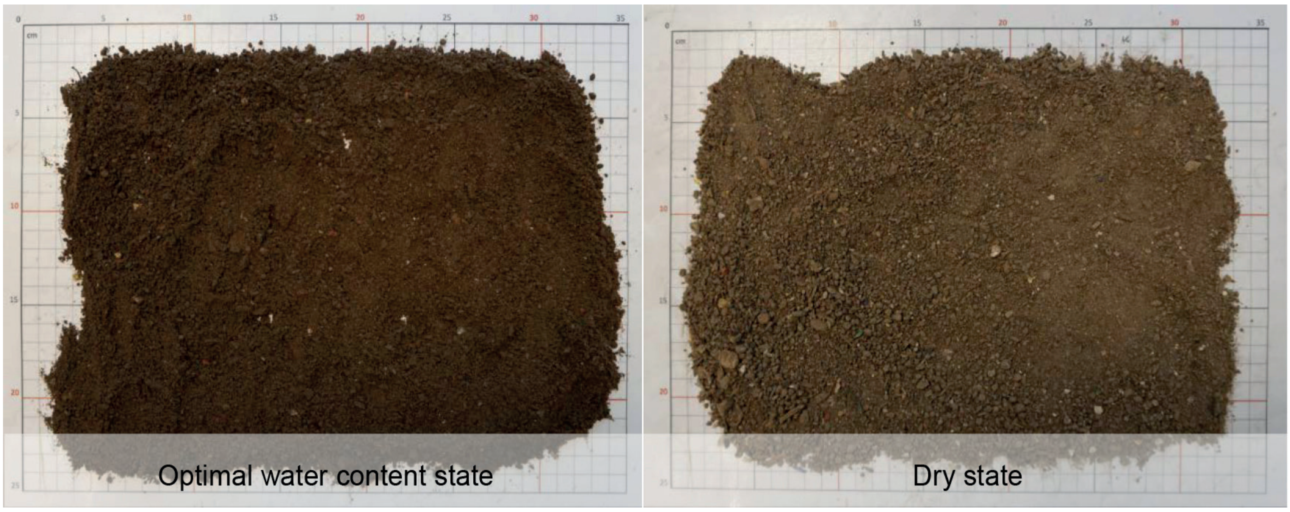

FIGURE 10: "Soil-like material" fraction in the optimal water content and dry states.

and 0.2-0.5 wt.% "Non-Fe metals" were obtained in the optimal water content state, while amounts of 41.9-43.9 wt.% "Fine fractions <4.5 mm (Soil-like material)", 35.9-39.0 wt.% "Inert", 7.4-10.0 wt.% "Combustibles", 1.2-1.8 wt.% "Fe metals" and 0.2-0.4 wt.% "Non-Fe metals" were generated in the dry state. These figures agree with the amounts determined in the material characterization of the fine fractions. Hence, it can be stated that the tested mechanical processing succeeded in sorting the fine fractions into the targeted grouped material fractions in an effective and efficient manner. Additionally, results suggest that a significant total amount of the fine fractions could be recovered through the implemented mechanical processing approach, which might contribute to the overall economic and environmental feasibility of the project in case of implementing full scale (E)LFM at the MSG landfill.

In general, the grouped material fractions recovered in the optimal water content state presented a higher amount of surface defilements and agglomerates (i.e. impurities) than in the dry state, from which fractions "Fe metals" and "Combustibles" seemed to be the most affected. Particle size range 30-10 mm appeared to be the most affected by the presence of water, while particle size range 90-30 mm was least affected. Dust generation and material losses were also influenced by the presence of water, which presented a slightly lower amount in the optimal water content state than in the dry state. Particle size ranges 90-30 mm and 30-10 mm yielded most of the recovered material, and particle size range 10-4.5 mm could be a relevant source of "Inert" fraction, as well as provide an additional amount of "Combustibles". A total amount of over 10 wt.%, distributed among all grouped material fractions of particle size range 10-4.5 mm, was additionally obtained by processing the fine fractions until a particle size of 4.5 mm.

It can be concluded that the real amounts of each grouped material fraction to be recovered from the fine fractions correspond to those obtained in the dry state, as well as the real material distribution according to particle size range. Discrepancies between the amounts obtained in the optimal water content and dry states can be mainly attributed to absorption/adsorption of water by the different types of materials present in each grouped material fraction. Additionally, these discrepancies can be due to the presence of surface defilements and agglomerates among the different grouped material fractions and particle size ranges, which in turn can affect the properties of certain materials (e.g. shape, mass and density), as well as the performance of sorting processes (e.g. particle size and density classification, magnetic and eddy-current separation and sensor-based sorting). The presence of impurities can also decrease the quality of certain materials, since they can be associated with the presence of heavy metals and organic pollutants. This could undermine the potential for the valorization of such materials in WtM and WtE schemes. However, discrepancies between both the optimal water content and dry states in this study were found to be negligible with respect to the success of the mechanical processing to separate the fine fractions into the different grouped material fractions. Nevertheless, laboratory analyses are yet to be performed in order to evaluate the effects, in terms of quality, of the greater amount of impurities present in the fractions obtained in the optimal water content state than those in the dry state. Moreover, laboratory analysis of outputs "Combustibles", "Inert" and "Fine fractions <4.5 mm (Soil-like material)" will determine if these fractions can be used for the intended purposes (i.e. alternative fuel, substitute for construction aggregates and substitute for soil in construction applications, respectively) or if further treatment might be necessary.

It is important to note that the mechanical processing approach tested in this study was carried out by means of small- and pilot-scale equipment, and results may differ substantially in large-scale machinery. Furthermore, the results of this study are case specific and much attention must be paid to several factors when transposing this information for the purposes of future investigations and full-scale applications. Moreover, it is worth stressing that the current market value of secondary raw materials, such as substitutes for construction aggregates and soil in construction applications, can be very low or even have negative values, as is the case with RDF in some countries. Additionally, the extent of the mechanical processing of the fine fractions is directly proportional to its cost and highly concatenated with the quality of its outputs. Besides, usually most of the landfill-mined material corresponds to fine fractions and, hence, they can hardly be left out of the scope of (E)LFM projects. Therefore, the profitability of (E)LFM is directly linked to a successful recovery of materials and energy from the fine fractions. Hence, the mechanical processing of the fine fractions is to be designed in such an optimal way that the applicable quality standards of the desired outputs can be met, and capital and operational expenditures do not hinder the viability of the whole project.

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8 MONT-SAINT-GUIBERT CASE STUDY: APPLICATION OF SENSOR-BASED SORTING IN THE FINE FRACTIONS

Scientific article no. 7: “Potential of Sensor-Based Sorting in Enhanced Landfill Mining”

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Annotation on my personal contribution to this scientific article:

As part of the mechanical processing of the fine fractions, I conceptualized and planned the tests regarding the fine fractions together with Bastian Küppers. The tests involving the fine fractions were carried out by me with support and guidance provided by Bastian Küppers. I participated in the analysis of the results of the tests carried out with the fine fractions, as well as in their interpretation. I also collaborated in the review and revision of the article.

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POTENTIAL OF SENSOR-BASED SORTING IN ENHANCED LANDFILL MINING

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ABSTRACT

In landfill mining, simple technologies and processing chains are frequently applied to excavated material in order to extract recyclable metals and high-calorific fractions used in energy recovery. Sensor-based sorting is one way to extract more and better material from a landfill. Two testing series have been performed using state-of-the-art technology to assess the technical feasibility of classifying and sorting landfill material with the aid of near-infrared spectroscopy. Fractions were classified as inert and combustible and sorted by particle sizes ranging from 90-30 mm, from 30-10 mm and from 10-4.5 mm for water content levels of 0 wt% and of 15 wt%, respectively. Additional tests were applied different landfill mining materials. Polypropylene (PP), polyethylene (PE) and polyvinyl chloride (PVC) products were produced, using sensor-based sorting, from a mixed fraction of particle sizes ranging from 60-200 mm. Both test series applied air-classified heavy fractions gained from two distinct processing schemes of landfill mining projects in Belgium and in Austria. Results show that the separation and classification of inerts and combustibles is feasible, enriching inert fractions with purities of 97.7 wt% to 99.6 wt% derived from inputs whose inert contents achieved 85.6 to 98.8 wt%. Efficient sorting is a function of the level of pre-processing, water content, relative amounts of adhesive fines, input composition and particle size ranges of the input material. Results from the second test series show that PP, PE, PVC and other materials can be successfully distinguished, achieving correct classification and ejection into respective product fractions of 91.8-99.7 wt%.

1. INTRODUCTION

In the past, landfills were considered cost-effective and final means of waste disposal (Krook et al., 2012). Nowadays such landfills pose both a problem and a chance. Spatial constraints, landfill-based hazards like leachate and methane emissions (Danthurebandara, M. et al., 2015) and shortage of landfill volume (Wörrle, J., 2018) can be arguments in favour of landfill mining (LFM) activities (Quaghebeur et al., 2013, Mor et al., 2006, Sormunen et al., 2008).

LFM is usually expensive and not economically feasible. Economic feasibility could be achieved, however, by using mechanical processing to recover marketable valuable materials. Since the 1950s, LFM projects have mostly applied simplified process chains using a screening stage and optional subsequent air classification and magnetic separation, among other processes, to render mechanical processing as cost-effective as possible (Krook, J. et al., 2012). As a consequence, only limited amounts of landfill resources (metals and refuse-derived fuel (RDF) could be recovered in the past (Krook et al., 2012). This limitation may be due to the fact that the reduction of environmental impacts and landfill remediation commonly has been given preference to the recovery of land or of landfill volume (Danthurebandara et al., 2015).

By contrast, the design of enhanced landfill mining (ELFM) is targeting the extraction of valuable materials for recycling (waste-to-material, WtM) and for energy production (waste-to-energy, WtE). The TönsLM project, for instance, has developed and examined scenarios based on rather complex process chains and innovative technologies. In addition to comminution, ballistic separators, screening and magnetic separation, also eddy current separators and near-infrared (NIR) sorters were considered in processing (Breitenstein et al. 2016), enabling higher and

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purer yields of recyclables. This resulted in better market prices, facilitating economically improved mining.

Studies have shown that ELFM is mainly inspired by the recovery of landfill volume and by the extraction of metals and of high-quality combustible fractions (Danthurebandara et al., 2015, Jones et al., 2013, Kieckhäfer et al. 2017). Most published ELFM projects so far are still at the planning stage, however. One main caveat of any practical implementation of (E)LFM projects is the risk that expected costs may exceed the achievable profit (Kieckhäfer et al. 2017). If framework conditions for ELFM should change, the mining of landfills will become more attractive to landfill operators (Kieckhäfer et al., 2017). This paper intends to shed more light on the potential recovery of recyclable and energetically valuable materials.

Utilization of the high-calorific fraction derived from (E)LFM has been practically tested in the recent past (Rotheut and Quicker, 2017; Wolfsberger et al., 2015). The relative amount of heavy metals contained in a high-calorific fraction limits its use in Austrian co-incineration plants (Wolfsberger et al., 2015). Since the distribution of heavy metals in the individual groups of substances and particle size ranges may vary significantly, suitable pre-treatment (separation of fractions contaminated with heavy metals) can prevent exceeding the limit values (Wolfsberger, T. et al, 2015, García López, C. et al., 2018).

Studies of Rotheut, M. and Quicker, P. (2017) concerning the energetic utilisation of RDF from LFM have shown that also the RDF's properties may vary a lot, affecting in particular calorific value, water and ash contents. Material from the 'Pohlsche Heide' landfill was excavated, for example, and processed in a state-of-the-art mechanical-biological waste treatment plant. Once the metals had been removed, the light fraction recovered using air classification was thermally converted into RDF. Calorific values between 9.2 and 23.9 MJ/kg, ash contents of up to 49.6% and water contents of 9.1% to 30% were observed. These findings as well as the sometimes high chlorine content caused the fuel properties of the examined material to be ranked as troubling.

Regarding mono-combustion of high-calorific fractions from LFM, the relative amounts of HCl and SO_2 included in the raw gas have been observed to exceed customary process values. In addition, the generation of steam has varied strongly while the bottom ash has shown finer particle size distributions and increased contents of Cl in the eluate. In clean gas, the only elevated readings related to the relative amount of HCl. Based on these and further experiments the authors conclude that co-combustion of RDF from LFM with RDF from municipal solid waste (MSW) in a 1:1 ratio seems feasible while mono-combustion of non-pre-treated material remains troubling (Rotheut and Quicker, 2017).

Mechanical recycling and other options, such as gasification, pyrolysis and hydrogenation, can only be pursued if more elaborate pre-treatment (cleaning, drying, comminution and thorough sorting) takes place (Zhou et al., 2014). The waste-to-energy (WtE) route is expected to be a plausible method of utilising high-calorific fractions from (E)LFM (García López et al., 2018; Quaghebeur et al., 2013) while a waste-to-material (WtM) route is not considered promising due to the increased levels of contaminants in recyclables (Quaghebeur et al., 2013). Generating potential RDF (pRDF) of a quality sufficient for (co-)combustion from (E)LFM requires the separation of material classes containing contaminants like PVC (chlorine), minerals (increased ash content) and metals.

Compared to the calorific fractions, recycling inert constituents such as metals, glass, ceramics and stone is estimated to be more promising (Quaghebeur et al., 2013). Mechanical processing, e.g. the separation of wood, paper and plastics from inerts, is required in this case, either to reduce the TOC or the Cl content of fractions intended for construction aggregates.

Sensor-based sorting (SBS) can be utilised to separate impurities from the respective fractions (pRDF and inert) in order to comply with the boundaries of both the high-calorific fraction and the inert fraction. One promising approach is the treatment of 3D or heavy fractions derived from air classification or ballistic separation. Generating suitable products from an ELFM process may require carrying out not only single but also multi-stage sorting steps (cascading application of SBS technology). In this way, several types of plastics can be separated, resulting in pure product fractions. Near-infrared technology was found helpful both for distinguishing inert from pRDF and for differentiating types of plastic that then could be separated using compressed air blasts (Kieckbehäfer et al., 2017; Beel, 2017).

Flawless functioning of SBS units is achieved by pre-treating LFM material. An important step of preconditioning is drying the landfill material, hopefully to improve subsequent mechanical processing (García López et al., 2018). Contaminants such as fine adhesions and coarse particles should be separated and fractions of processable particle size ranges produced using pre-classification. The resulting particle size ranges have to match machine requirements of subsequent processing units. In addition, this classification can be used to subdivide the material flow into volume and mass flows suitable for further treatment, preventing overloading of the downstream processing equipment. Pre-processing can also be used to enrich the valuable substances or to separate contaminants into specific grain size ranges and material flows (Pretz and Julius, 2008).

If the treatment is carried out on a landfill site, SBS technology must be adapted to adverse environmental conditions. The treatment can be affected by weather conditions or by dust, raising the risk of e. g. soiling on light bulbs that would cause malfunction or impairment of the SBS equipment (Gundupalli et al., 2017).

This paper discusses near-infrared-(NIR)-based sorting since this technology provides a wide range of possible applications. However, NIR sensors can only analyse the surface of particles and are therefore particularly susceptible to external contamination and adhesions (Pomberger and Küppers, 2017). That is why research regarding the application of this technology in LFM is of particular interest. Two applications for NIR SBS technology are examined:

- Enrichment of the inert fraction using the separation of

combustibles (plastics, paper, cardboard, wood, etc.);
- Distinction and separation of various types of plastic from a LFM process to create unpolluted fractions.

To verify the technical feasibility of these applications, the distinctness of combustibles, inerts and impurities is examined and quantified.

2. MATERIALS AND METHODS

ELFM projects were conducted at Mont-Saint-Guibert (MSG), Belgium, and on the Halbenrain landfill, Austria. Excavations and mechanical processing in MSG were carried out to verify the suitability of a ballistic separator as the first processing unit in the mechanical processing of LFM material. In Halbenrain, the purpose of on-site examinations was to test whether the available mechanical biological treatment plant was able to process LFM material.

At the MSG landfill, municipal solid waste (MSW) and construction and demolition (C&D) waste were disposed of between 1958 and 1985. For the purposes of this examination, the top clay layer was removed first. Next, a total of about 425 m³ of landfill material was excavated in four batches and treated with the ballistic separator (STADLER STT 6000). The LFM material was processed in two stages, using mesh sizes of 200 mm and 90 mm to produce five output streams (cf. Figure 1). Detailed information concerning landfill site, processing, sampling and landfill composition is provided by García López et al. (2019) and Hernández Parrodi et al. (2019).

The fine fractions samples (<90 mm), gained during ballistic separation, were divided into two fractions and treated at two different water content levels (0 wt% and 15 wt%) or using screening into the grain size ranges of 90-30 mm, 30-10 mm, 10-4.5 mm and <4.5 mm, followed by air classification. Heavy fractions from air classification (90-30 mm, 30-10 mm and 10-4.5 mm) yielded input material for SBS experiments and were therefore drawn on during the examination.

At the Austrian Halbenrain landfill, about 500 t of LFM material were excavated and processed in an on-site mechanical and biological treatment plant in 2016 to study options for RDF and metal recovery. The treatment included three to four weeks of biological drying in rotting boxes, followed by shredding, multiple screening stages (screen cuts: 200 mm, 60 mm, 14 mm), separation of ferrous and non-ferrous metals using magnetic and eddy current separation and, finally, air classification. More detailed information is provided by García et al., 2018.

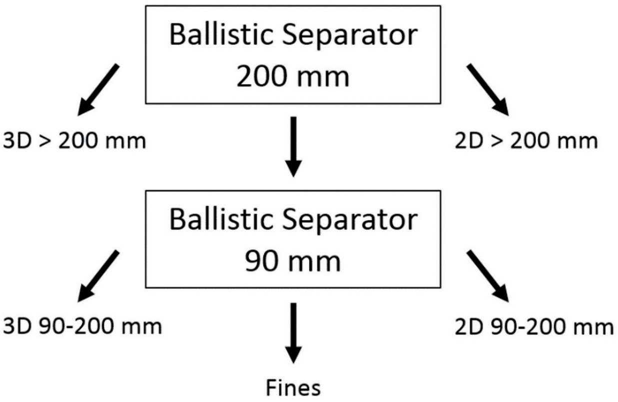

FIGURE 1: Procedure for mechanical treatment of landfill material in MSG.

For SBS examinations, samples were taken from the heavy fraction of 200-60 mm. These samples were handpicked and all particles (1377 pieces) categorised by visual inspection and Fourier Transformed Infrared Spectroscopy (FTIR, Agilent Technologies, Cary 630) according to material types: polypropylene (PP), polyethylene (PE), polystyrene (PS), polyvinyl chloride (PVC), polyethylene terephthalate (PET), and residuals.

A hyperspectral imaging (HIS) near-infrared chute sorter (sensor: EVK HELIOS NIR G2 320, spectral range 990-1700 nm) was used for performing the SBS experiments. The spectral resolution of the sensor was 3.18 nm, its spatial pixel width being 1.60 nm. The frame rate of the line sensor was 476 Hz for an exposure time of 1800 µs. During the experiments, the side of a spatial pixel in the direction of movement was always less than 1.6 mm long. Sorting recipes were created by recording sample objects of each material class. Two recipes emerged:

- Recipe 1 – for treating fractions of 90-30 mm, 30-10 mm and 10-4.5 mm from MSG (objective: separation of combustible from inert materials of the heavy fractions);
- Recipe 2 – for treating air-classified heavy fractions from the Halbenrain landfill (objective: distinction of plastic types PP, PE, and PVC from PS, PET and residuals).

Recordings of the recipes contained spectra allocated to pixels on all sample objects. Spectra from several pixels were collected and an average spectrum for each material was created. These spectra were used as references for classifying object pixels. The classification of different materials was improved by including only such wavelength ranges that displayed significant differences (cf. Figures 2 and 3). As a result, a pseudo-colour was allocated to each object pixel. All objects were then assigned to the material class represented by the predominant pseudo-colour. Particles were separated using air blasts from a compressed air nozzle bar to validate the sorting efficiency of the recipes. Low throughputs were applied to avoid overlapping objects, allowing to quantify correct classification rates unaffected by variations of the throughput.

The spectra used in recipe 1 are given in Figure 2. In total, 16 spectra of pulp-based materials (wood, paper and cardboard) and bone (red), plastics (green) and inerts (blue) were used for this recipe. Wavelength ranges included in the classification cover 1120-1273 nm, 1342-1527 nm and 1618-1674 nm (areas marked red in Figure 2). Soot-blackened plastics cannot be classified by spectral data reflected in the NIR range since they absorb much of the irradiation. Their classification as plastics was facilitated by using the low intensity of reflected radiation.

For evaluating the results of trials based on recipe 1, an

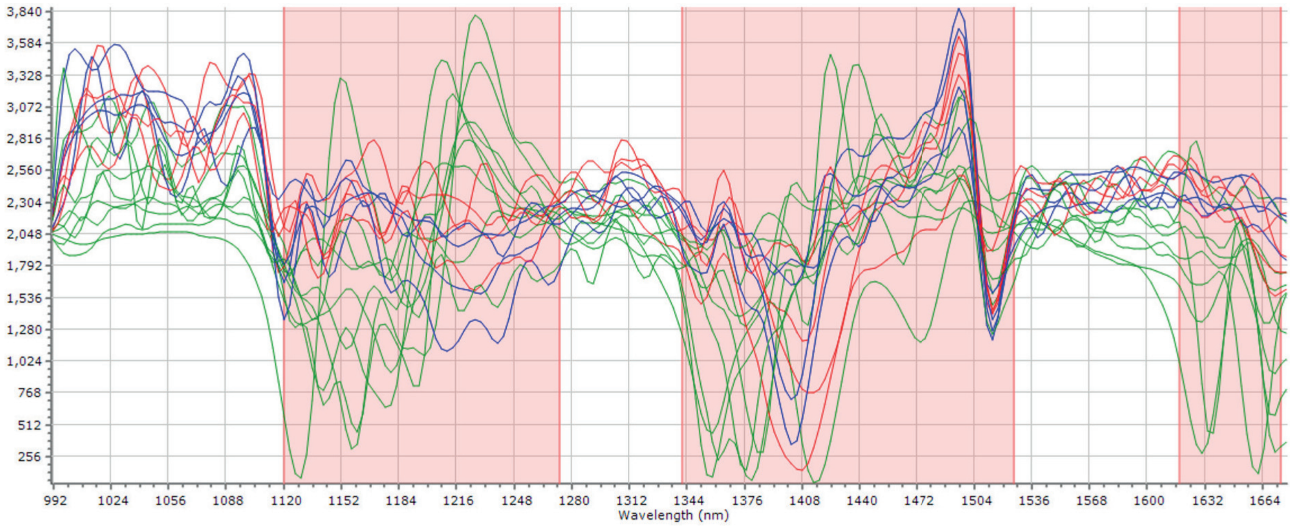

FIGURE 2: Spectral data used to distinguish inerts (blue) and combustibles, consisting of pulp (red) and plastics (green).

enrichment ratio was calculated to assess the separation efficiency of combustibles and inerts. For this purpose, the purity of a product fraction (inert content in inert product or combustibles content in combustibles product) was divided by the content of the respective material class in the input fraction. If the enrichment ratio was 1 or higher, the material class was enriched via sorting.

Spectra used for the constituent separation of PP, PE and PVC from PS, PET and residuals based on recipe 2 are given in Figure 3. In total, 7 spectra of PP (blue), PE (red) and PVC (green) were applied. Wavelength ranges included in the classification cover 1120-1242 nm, 1339-1414 nm and 1636-1671 nm (areas marked red in Figure 3). To prevent erroneous classification of PVC as PP or PE, soot-blackened plastic was always classified as PVC, based on the low intensity of radiation reflected by such particles. Neither spectra of PS nor of PET or residuals were stored in recipe 2.

For assessing the correct classification rates based on recipe 2, both mass-based (wt%) and particle-based (p%) approaches were examined. For the mass-based approach, the weight of each material class in the eject and reject fraction entered the calculation of yield by material. For the particle-based approach, the numbers of particles in the eject and reject fractions were counted and entered the calculation of yields by material type in a product. Multiple experiments were performed to reduce the effects of outliers due to atypical positioning and mechanical errors from atypical motions of objects during the sorting process. For each trial, all particles were analysed and sorted anew.

3. RESULTS AND DISCUSSION

The results of trials separating inerts and combustibles are given in Table 1. Data on the composition of input and output fractions is given separately for trials based on water contents of 0 wt% and of 15 wt%. Comparing the composition of all input fractions demonstrates that the inert content rises with decreasing particle size range for both water content levels. Especially material in the frac-

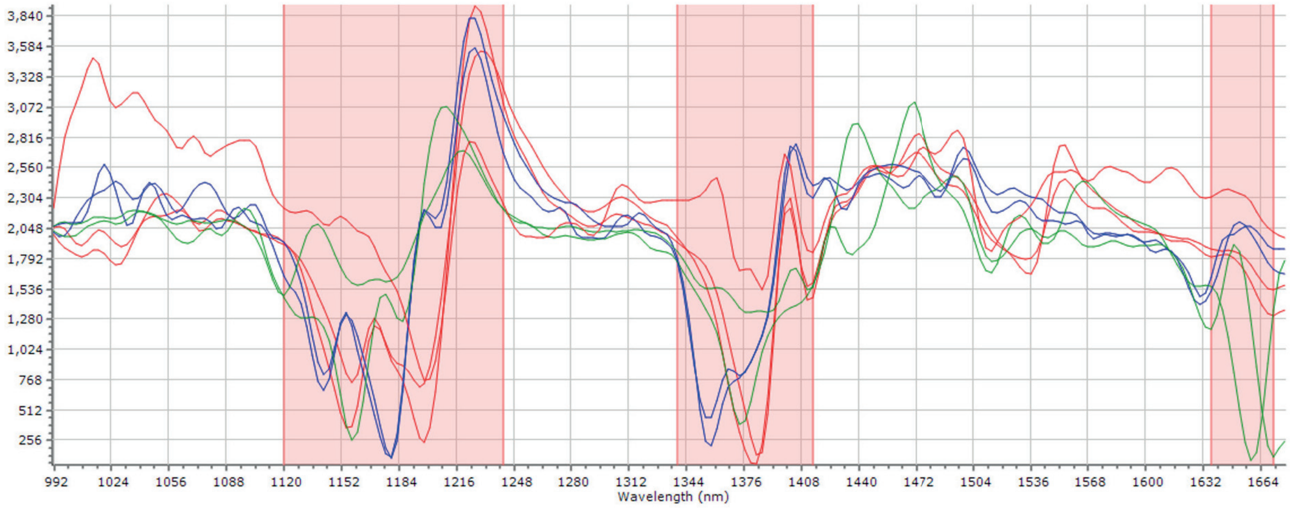

FIGURE 3: Spectral data stored in recipe 2 for distinguishing PP (blue), PE (red) and PVC (green) from PS, PET and residuals.

TABLE 1: Results of sorting trials with Recipe 1.

Water Content [wt%]	0			15		
Particle size range [mm]	90-30	30-10	10-4.5	90-30	30-10	10-4.5
Input						
Inert content [wt%]	88.2	97.1	98.1	85.6	93.7	98.8
Combustibles content [wt%]	11.8	2.9	1.9	14.4	6.3	1.2
Reject - Inert Fractions						
Purity - Inert [wt%]	99.3	99.7	98.8	99.6	97.7	99.4
Yield of inerts [wt%]	99.7	97.8	99.0	99.8	95.1	99.5
Enrichment ratio	1.126	1.027	1.007	1.164	1.043	1.006
Eject - Combustibles Fractions						
Purity - Combustibles [wt%]	62.0	26.3	36.3	68.9	31.3	49.5
Yield of combustibles [wt%]	94.7	72.2	99.0	97.4	66.8	53.6
Enrichment ratio	5.254	9.069	19.105	4.785	4.968	41.250

tion of 90-30 mm contains significantly more combustibles than material in smaller particle size ranges.

The relative content of combustibles in the input is higher for the water content of 15 wt% in particle size ranges of 90-30 mm and of 30-10 mm than in samples containing a water content of 0 wt%. This observation can be explained by higher water absorption in combustibles compared to inerts and increased content of adhesive fines due to the wet surface of combustibles.

All trials achieved high purities for inert fractions (97.7-99.7 wt%) while the purity of combustible fractions was comparatively low (26.3-68.9 wt%). Yet enrichment ratios are low for inert (1,006-1,164) and high for combustibles (4.785-41.250). These results can be attributed to the low content of combustibles in all input fractions, enabling high enrichment ratios, while high inert contents in the input fractions limit enrichment ratios. Rather low purities of combustibles in the respective product fractions can be explained by inert losses wrongly classified and ejected as combustibles. Due to the high amounts of inerts in input fractions, even minor loss of inerts can strongly impact the combustible fractions. The purity of generated combustible fractions could be further improved by applying multiple sorting stages, enriching the combustible fraction even more; the economic feasibility of this approach, however, is in doubt.

The enrichment ratios for inert fractions decrease with particle size while the enrichment ratios of combustibles increase. This is mainly associated with the decreasing relative amount of combustibles in the input for small particle size ranges. For instance, a water content of 0 wt% produced neither a lesser yield of inerts nor of combustibles for the particle size range of 10-4.5 mm, compared to the sorting results of the 90-30 mm fraction. Still, the enrichment ratio of inerts drops with decreasing particle size while the enrichment ratio of combustibles rises.

Although a water content of 15 wt% produces a proportionally lesser yield of combustibles with decreasing particle size, the combustibles enrichment ratio for the particle size range of 10-4.5 mm is highest at 41.250, which is more than twice the respective value for a water content of 0 wt%. This is mostly due to the fact that the lower combustibles content in the input and the 0.5 wt% higher yield of inerts for a water content of 15 wt% have more impact on the sorting efficiency than the yield of combustibles would.

Misclassification, mostly of combustibles but to some extent also of inert, can mainly be referred to faulty classification of pulp material. These particles were characterised by high amounts of adhesive fines on the surface. Such adhesives can impair the spectra, e. g. of paper, resulting in a mixed spectrum of inert and paper. This effect can also be observed in Figure 2 as spectra of pulp-based particles look similar to inert spectra due to their contamination with adhesive fines. The adverse effect of adhesives on SBS is best demonstrated for a water content of 15 wt%, due to increased amounts of adhesives. The yield of combustibles drops with particle size. Especially for the fraction of 10-4.5 mm, major quantities of adhesive fines could be observed on particle surfaces (compare Figure 4).

The sorting results of all trials involving Halbenrain material are given in Table 2. To evaluate the classification and sorting efficiency independently from input composition, only the yield of PP, PE and PVC products is given for each fraction. Results show the average yield of each material class over five runs.

Results of sorting trials show that the particle- and mass-related yields correlate significantly. Differences can be attributed to differing particle masses.

While generating the PP product, neither PVC, PS nor PET were wrongly classified and sorted. Less than 0.8 p% (0.6 wt%) of PE and residuals were falsely ejected.

When sorting out the PE product, the primary misclassification observed was that of PP as PE (3.2 p%/2.1 wt%) while the ejection of PVC, PS and residuals stayed always below a level of 0.8 p% (0.3 wt%), partly due to gliding particles (PS). No misclassification of PET was observed.

While producing the PVC product, an increased misclassification of PP (4.4 p%/2.7 wt%), PE (11.0 p%/8.8 wt%) and residuals (5.1 p%/3.5 wt%) was observed which can be attributed to the classification of soot-blackened particles as PVC. No PET was misclassified and discharged as PVC.

An overall distinction between plastic types and separation of such material fractions from LFM could be per-

FIGURE 4: Reject (left) and eject (right) from SBS trial, water content 15 wt%, fraction 10-4.5 mm.

formed using SBS technology. The relatively high accuracy rates achieved, despite misclassification due to soot-blackened particles, can be explained by the preceding comprehensive biological and mechanical processing as well as by the coarse particle grain size of the examined material, resulting in low amounts of water and adhesives on particle surfaces and enabling mostly correct classification and sorting results.

However, further multiple sorting stages and treatments (cleaning, drying, etc.) will be necessary to meet the requirements of recycling and not only those of WtE.

4. CONCLUSIONS

NIR-based SBS trials using pre-treated landfill material show promising results for the application of this technology in ELFM. The separation of inert and combustibles and the distinction between specific types of waste plastic was successfully demonstrated. Sorting efficiency is affected by the level of pre-processing, the water content and the relative amount of adhesive fines, the material composition and the range of particle sizes of the input material at the SBS stage.

While a decent identification of plastic types (except for soot-blackened plastics) using NIR spectroscopy is possible, detecting pulp-based particles and distinguishing them from inerts was sometimes impaired for particle size ranges <30 mm due to adhesive fines, particularly when water was present.

Whether any long-term stability of a sufficiently effective SBS process can be achieved under plausible processing conditions has to be tested at large-scale. Problems, e. g. due to dust formation or various degradation states of plastics, may decrease the efficiency rates attained so far. In such cases it might be necessary to adapt the algorithm for material classification.

TABLE 2: Yield of PP, PE and PVC products from Halbenrain LFM air-classified heavy fraction – average of 5 runs.

	PP product	PE product	PVC product
PP yield	94.1 p%	3.2 p%	4.4 p%
	94.8 wt%	2.1 wt%	2.7 wt%
PE yield	0.8 p%	92.9 p%	11.0 p%
	0.6 wt%	91.8 wt%	8.8 wt%
PVC yield	0.0 p%	0.2 p%	95.2 p%
	0.0 wt%	0.1 wt%	99.7 wt%
PS yield	0.0 p%	0.8 p%	0.8 p%
	0.0 wt%	0.3 wt%	0.7 wt%
PET yield	0.0 p%	0.0 p%	0.0 p%
	0.0 wt%	0.0 wt%	0.0 wt%
Residuals yield	0.4 p%	0.4 p%	5.1 p%
	0.3 wt%	0.2 wt%	3.5 wt%

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9 MONT-SAINT-GUIBERT CASE STUDY: QUALITY ASSESSMENT OF RECOVERED NON-FERROUS METALS FROM THE FINE FRACTIONS

Scientific article no. 8: "Quality Assessment of Nonferrous Metals Recovered from Landfill Mining: A Case Study in Belgium"

Lucas, H.I., Garcia Lopez, C., **Hernández Parrodi, J.C.**, Vollprecht, D., Raulf, K., Pomberger, R., Pretz, T., Friedrich, B., 2019. Quality Assessment of Nonferrous Metals Recovered from Landfill Mining: A Case Study in Belgium. Detritus 8 (1), 79–90. 10.31025/2611-4135/2019.13879.

Annotation on my personal contribution to this scientific article:

The samples of the non-ferrous metals recovered from the fine fractions were provided by me, as well as the information regarding their main characteristics. I collaborated in the preparation of the article and in the analysis of the data and evaluation of results. Also, I assisted Hugo Lucas with the review of the article.

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QUALITY ASSESSMENT OF NONFERROUS METALS RECOVERED BY MEANS OF LANDFILL MINING: A CASE STUDY IN BELGIUM

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ABSTRACT

Nonferrous metals (NFMs) provide a major contribution to potential revenues generated by the implementation of landfill mining (LFM). However, metals present in landfills undergo stronger degradation than during regular use, likely resulting in a lower quality compared to conventional scrap. Nowadays, information relating to the most common metals found in LFM projects is readily available, although no consistent quality data can be attained. In general, excavated landfill material is processed mechanically through a series of different steps, including screening and metal separation by magnetic and eddy current separators. This study focuses on the characterisation of NFMs recovered from a specific landfill site in Belgium, with the aim of assessing the quality of each NFM for marketing purposes. The study also addresses the issue of metal concentration and defilements detected, with a preliminary evaluation indicating a total of 5 kg of NFMs per ton of excavated material processed at the Mont-Saint-Guibert landfill. In addition, the application of thermal treatment enabled the observation that, on average, only 70 wt% of the nonferrous fraction is metallic. The majority of surface defilements (30 wt%) are represented by a combination of organic and inorganic impurities that are strongly bound to NFMs. Consequently, the different scraps extracted and the eventual destination of each were technically assessed using two separate approaches. The first approach facilitated the potential recovery of seven types of scraps from NFMs, including two different qualities of Al scrap, two of Cu, one of Pb, one of Zn, and one of stainless steel. In line with the second, and perhaps more realistic approach, NFMs may be directly marketable from the landfill as mixed nonferrous scrap.

1. INTRODUCTION

NFMs such as Cu, Al, Zn, Pb, Cr, Ni, Ag and Au, are distinguished from ferrous metals (FMs) based on their low or zero magnetization when in the proximity of a magnetic field. NFMs are perhaps the most valuable secondary raw material found in several types of waste, including electronic waste, construction and demolition (C&D) waste, industrial waste, and municipal solid waste (MSW). Many NFMs are considered strategic metals in Europe (Roadmap to a Resource Efficient Europe) and used in countless applications. Accordingly, the European Commission has prioritised sustainable access to critical raw materials through the recycling and reuse of waste.

In the field of NFM sorting, eddy current separators (ECSs), dense media separators (Barker, 2014) and hand sorting (Capuzzi and Timelli, 2018) are commonly employed. Furthermore, sorting technologies have been developed to automate and optimise the sorting processes: X-ray fluorescence (XRF), colour sorting and X-ray tomography (XRT) can be used for different qualities of Cu, Al, Pb, Zn and stainless steel scrap (Dürkoop et al., 2016; Schlesinger, 2013; Schlesinger et al., 2011).

The valorisation of scraps from non-conventional sources such as, for instance, MSW, C&D, or even landfilled waste (LFW) indicates the need for a detailed understanding of both the concentration and quality of the metals and the number of steps or techniques applied to separate the latter into different metal categories and grades. For example, Soo et al. (2019) investigated the influence of different sources of Al-scraps from an aluminium recycling facility in Belgium demonstrating how the quality obtained was linked to particle size and metal source.

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Several authors have highlighted the accumulation over time in a large number of landfills of a vast quantity of materials, which might be suitable for use as potential secondary resources (Kapur and Graedel, 2006; Lifset et al., 2002; Muller et al., 2006; Quaghebeur et al., 2013). For example, according to Krook et al. (2012), the amount of Cu landfilled worldwide is comparable to the existing stock in use within the technosphere. Likewise, Cohen-Rosenthal (2004) reported an amount of Al and steel stored in a site investigated corresponding to approx. 1,000 tons and 12,000 tons, respectively, per excavated hectare.

According to Winterstetter et al. (2015), and Van Vossen and Prent (2011), in addition to the most common economic drivers such as reclaimed land or avoidance of repeated landfilling costs, NFMs contribute extensively to the revenues of LFM. However, metals remain buried for several decades, potentially subjected to corrosion and pollution before being excavated from a landfill. There is a clear lack of information in the literature relating to metal concentration, quality and marketability of these scraps. Table 1 illustrates the number of metals found in several LFM projects, not all of which indicated the proportion of FMs and NFMs; indeed, only the Austrian LAMIS project indicated the actual concentration of the ferrous fraction obtained by mechanical processing after a pyrometallurgical trial using an induction furnace (Wolfsberger et al., 2015).

Therefore, the main research questions addressed by this study are:

- What is the actual concentration of NFMs, and what is the extent of surface defilements ?
- Can the recovered NFMs be commercialised and, if so, under what standard?

2. MATERIALS AND METHODS

2.1 Site description

NFMs analysed in this study were excavated from a landfill site located in the municipality of Mont-Saint-Guibert (MSG) in the province of Walloon Brabant, Belgium (Figure 1). This site covers an area of approx. 44 ha, which has been in operation since 1937 as a sand quarry and was transformed in 1958 into a disposal site for MSW, C&D waste and non-hazardous industrial waste (ISSeP, 2011). The excavation took place in the oldest part (red delimited area in Figure 1a) which covers a surface of 14 ha, storing circa 5.7 million m^3 of waste (Hernández Parrodi et al., 2019; IGRETEC, 1994).

For the purpose of this study, a small zone of circa 130 m^2 from the old part of the landfill (white delimited area in Figure 1b) was selected for excavation based on the results of the geophysical exploration (García López et al., 2018; Hernández Parrodi et al., 2019a).

2.2 Excavation works and material pre-processing

The selected area was excavated to a depth of approx. 5 m (excluding 4 m of cover layer) and roughly 370 ton of LFW extracted (Figure 2a). The excavated volume (425 m^3) was divided into four sub-volumes (batches 1-4) of 140 m^3, 100 m^3, 120 m^3 and 65 m^3, respectively. The batches were classified in situ according to type of waste. Batches 1 and 2 were mainly composed of MSW and C&D, while batch 3 was largely comprised of C&D and batch 4 MSW. These batches had previously been processed using a ballistic separator (Figure 2b) in two steps, producing three different outputs: 3D, 2D and under-screen fractions. In the first step, the ballistic separator used a screen of 200 mm, while

TABLE 1: Concentration of metals in previous LFM investigations (Hernández Parrodi et al., 2018).

Bibliography	Van Vossen and Prent, 2011 (various countries)	Kaartinen et al., 2013 (Kuopio, Finland)	Quaghebeur et al., 2013 (REMO, Belgium)	Wolfsberger et al., 2015 (Lower Austria, Austria)	Jani et al., 2016 (Högbytorp, Sweden)	Bhatnagar et al., 2017 (Kudjape, Estonia)	Garcia Lopez et al. 2018 (MSG, Belgium)
Type of waste disposed	Various	MSW	MSW	MSW	MSW+C&D	MSW	MSW+ C&D
Total metals	2.0%	3.0-4.0%	2.8 ± 1.0%	2.1-4.7%	1.0%	3.1%	2.9%

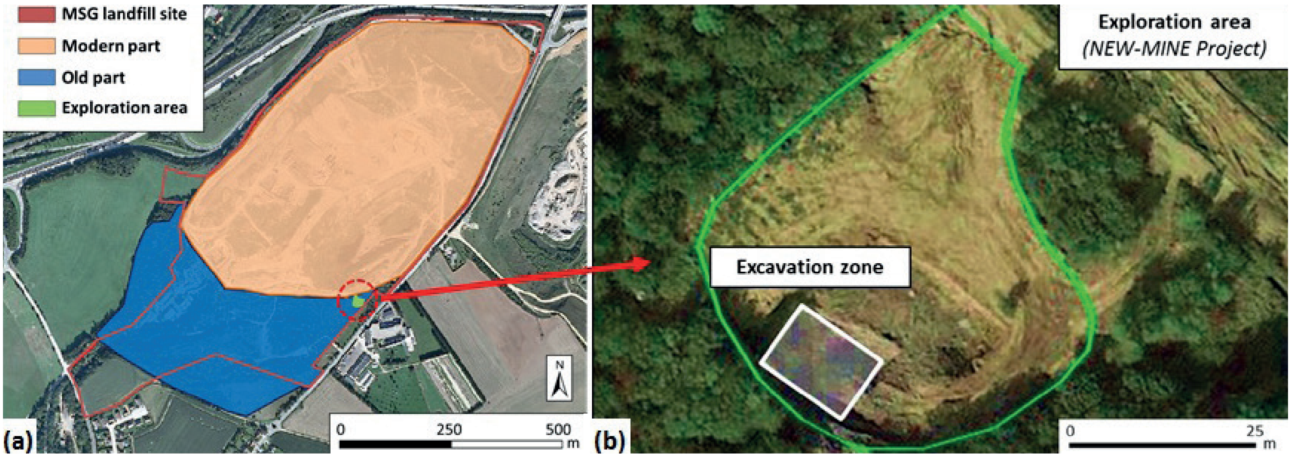

FIGURE 1: MSG landfill (a) and excavation zone (b) (Hernández Parrodi et al., 2019a).

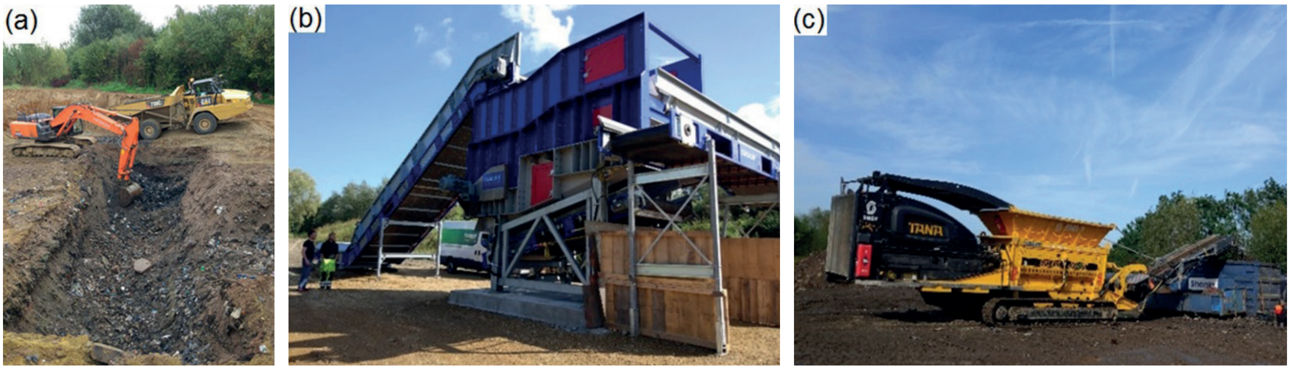

FIGURE 2: (a) Excavator and dumpster; (b) ballistic separator; (c) mobile shredder.

the second step was performed with a screen of 90 mm.

The under-screen fraction below 90 mm was defined as the fine fraction, whereas materials with a particle size ≥90 mm (3D ≥200 mm, 2D ≥200 mm, 3D 200-90 mm and 2D 200-90) corresponded to the coarse fraction. The 2D fraction from the first step of the ballistic separation (≥200 mm) was processed in situ using a mobile shredder equipped with a built-in over-belt magnetic separator (Figure 2c) to recover FMs. The rest of the material was sampled and subsequently processed. Further information about this landfill site and the characteristics of the excavated material can be found in García López et al., 2019, and Hernández Parrodi et al., 2019a.

2.3 Material processing

During the excavation, samples were obtained as prescribed by the German Directives LAGA-PN78 and LAGA-PN98. With the exception of the 3D fraction ≥200 mm, manually sorted in situ, the remaining fractions were first dried at 75°C (based on DIN CEN/TS 15414-1 to prevent loss of volatile matter and degradation of certain plastics) and then processed at the Department of Processing and Recycling (IAR) of RWTH Aachen University. Table 2 summarises the sampling of different fractions. A detailed description of the methodology and material composition can be found in García López et al. 2019 and Hernandez Parrodi et al., 2019b.

Different methods of metal extraction were chosen according to particle size. NFMs in the coarse fractions (200-90 mm and ≥200 mm) were retrieved manually following the recovery of FM using different types of magnetic separators. On the other hand, the fine fraction (<90 mm) was subdivided into three particle size ranges, i.e. 90-30 mm, 30-10 mm and 10-4.5 mm to enhance the recovery of FMs and NFMs using magnetic separators (over band and drum magnetic) and ECSs, respectively. The fraction <4.5 mm was not processed further for recovery of FMs and NFMs. Further details regarding the mechanical processing of fine fractions are reported in Hernández Parrodi et al. 2019b.

TABLE 2: List of processed samples.

Fraction	Nº of samples	Mass processed [kg]	Batches analysed
3D≥ 200 mm	Processed in-situ		
2D≥200 mm*	30	413	1, 2, 3 & 4
2D 200-90 mm	21	474	1, 2, 3
3D 200-90 mm	23	203	1, 2, 3
<90 mm	16	200	1 & 2

** Note: fraction shredded down to 275 mm*

NFMs from both coarse and fine fractions were separated further by manual sorting and divided into different categories: non-magnetic Fe scrap, Cu scrap, Al scrap, heavy scrap and unknown metals.

Following this preliminary separation, a portable XRF analyser (Thermo Fisher NITON XL3t 600) and a digital balance were used to analyse the chemical composition and weigh each metallic particle respectively in order to perform a quantitative analysis.

On average, almost 240 different metallic pieces were analysed, of which 74 wt% originated from the fine fractions. Based on their chemical composition and morphology, metal particles were organised into the categories listed in Table 3.

Figure 3 summarises the characterisation process carried out in this study from the excavation and mechanical processing outputs to the assessment of metallic scraps.

2.4 Assessment of metal quality

To assess defilements bound to NFMs and actual metal concentration, three different approaches were tested. The first method was based on ultrasonic cleaning as most of the impurities remained attached to the metals after cleaning for 20 minutes. The second approach was the same method used in the Austrian LAMIS Project (Wolfsberger et al., 2015) based on the smelting of scraps in a raw state. Smelting provides a detailed insight into the metal grade and alloy content, although providing only a rough estimation of defilements, as was the case with Al scrap recovered from MSG (Lucas et al., 2019). For example, Al has a high affinity for oxygen, and during smelting and casting lost around 50% of its mass as a result of oxidation (Samuel, 2003).

Carbon-rich defilements may act as reductants of metal oxides or favour the formation of carbides during smelting of different NFMs, which in many cases is critical and undesired. As an example, metal oxides such as Ti (i.e. from

TABLE 3: Classification of metal categories from NFM samples of MSG landfill.

Category name	Details
Al-foils	Foils of aluminium usually used for food preparation
Al-packaging	Used beverage cans (UBC), Tetrapack© and other aluminium packaging such as aerosol cans, aluminium wrapping, etc.
Al-alloy	Remaining aluminium particles found in waste, not included in Al-foils and Al-packaging
Brass	Metallic particles mainly composed of Cu and Zn
Cu-wires	Electric wires
Pb-alloy	Metallic particles in which Pb was the main element
Stainless steel	Nonmagnetic Fe-scrap containing elements such as Cr and Ni
Zn-alloy	Metallic particles in which Zn was the main element
Other metals	Rest of the metals found with a low frequency such as bronzes, silver alloys, iron scraps (mainly Fe-Sn food cans), nickel alloys, etc.

the coating of Al cans), Fe, Si, Zn, found in a vast number of natural minerals and soils can be easily reduced by Al during smelting and end up in the metallic phase as alloying (Schlesinger, 2013; Schmitz et al., 2006)

Finally, the best results were obtained using thermal treatment based on the de-coating process used by the Al industry in the treatment of used beverage cans (UBC) prior to smelting (Schmitz, 2006; XIAO et al., 2005). Al is potentially the NFM most heavily affected by thermal treatment due to its high affinity for oxygen. Indeed, literature reports

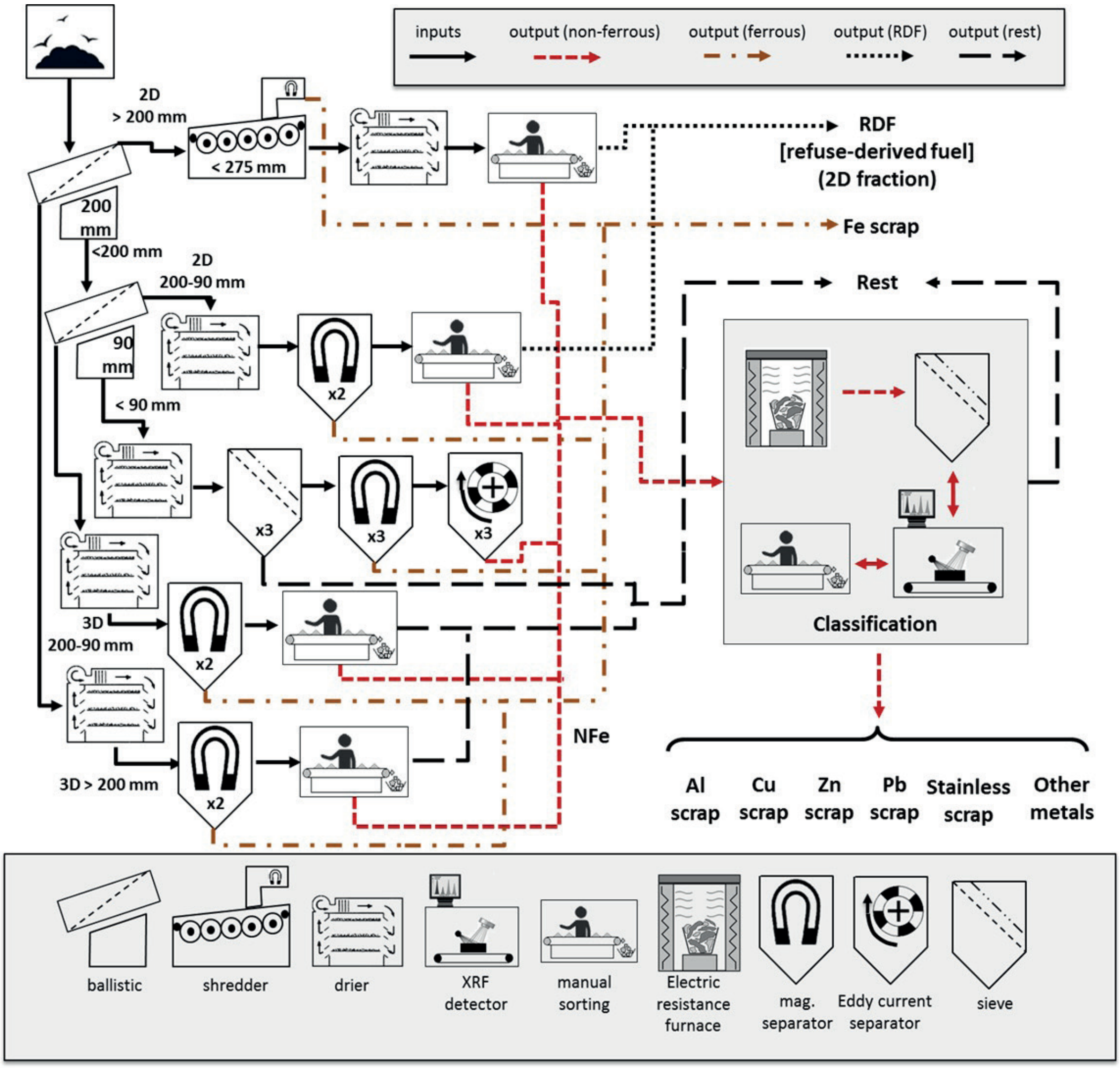

FIGURE 3: Scheme of NFM processing of excavated LFW.

recommend temperatures ranging between 400-450°C to minimise metal losses during this step (Schmitz et al., 2006). The treatment temperatures applied to NFMs were invariably below boiling point, with Al, Fe, Cu and other less common scraps, for instance, Ni or Ag, remaining unmolten during treatment. In addition to Al, the most critical scraps were those compounded mainly by Pb and Zn, which are liquid at 450°C. These materials, smelted separately, showed no critical degradation during treatment. With regard to other possible volatile compounds such as water or salt, scraps had previously been dried during the material processing, and as the melting point for the majority of salts is above 750°C, these compounds were not expected to volatilise during thermal treatment.

For the reasons stated above, the scraps listed in Table 3 were treated at 400/450°C for 30 min in an air atmosphere using an electric resistance furnace. A thermocouple type K placed inside the crucible guaranteed temperature control.

Scraps incinerated inside 0.4 litre-clay crucibles were weighed before and after thermal treatment using a high precision balance. Weight loss registered between the input and output of each incinerated scrap category was interpreted as the organic content. Following thermal treatment, outputs were sieved at 1 mm, washed and finally dried at 100°C for 24 hours. Large non-metallic particles such as rock, ceramics or glass were removed by hand. The weight difference between incineration output and cleaned metals was taken as inorganic content.

With regard to the marketability of metal scraps, it should be highlighted how industry standards are used as references in scrap trading. Several of these standards and their denomination codes are summarised in the Scrap Specifications Circular which is updated every year. However, no specific denomination has been coined for unconventional sources of mixed nonferrous scraps such as those originating from MSW or LFW. Hence, prices are subject to agreement between buyers and sellers, and essential aspects such as the variety of metals contained in the scraps, and the concentration and nature of defilement should be given due consideration, particularly as the number of separation steps and final destination of these metals are heavily dependent on the latter. For example, Soo et al. (2019) studied the influence of different Al fractions recovered from a Belgian recycling facility. In this study, fractions <12 mm and ≥40 mm exhibited a large number of undesired alloys (Fe, Cu, Zn, Si, among others) after smelting; moreover, a particular fraction mixed with Fe scrap was separated manually, increasing not only operative costs but also producing low Al grades with a marginal profit.

To date, the market is devoid of reference standards for scraps recovered from landfills. Using information collected from incineration outputs, seven potential marketable scraps that adhered closely to the standards applied in the scrap market were defined and are listed in Table 4.

Further to dividing NFMs into a series of different scrap categories, metal concentration should also be taken into account in order to estimate the potential value. In this study, the price of each scrap category ($P_{scrap}^{landfill}$) extracted from landfill was defined as the product between the price of the closed standard scrap ($P_{scrap}^{standard}$) listed in Table 5, divided by its concentration of metals ($M^{standard}$ pre-established in the Scrap Specifications Circular), and multiplied by the metal concentration of each pre-defined category ($M^{landfill}$). This methodology is summarised in equation 1.

$$P_{scrap}^{landfill} = P_{scrap}^{standard} \times M^{standard} \;/M^{landfill} \qquad (1)$$

3. RESULTS

3.1 Mechanical processing and manual sorting

Manual and mechanical sorting of ballistic separation output fractions revealed that metals represented 2.9 wt% of input material, with NFMs constituting only 16.5%.

Notably, the distribution of metals across particle size was largely similar to the distribution registered for input material (see Table 6), i.e. no particular abundance of metals across any of the particle size fractions.

Figures 4a and 4b illustrate the results obtained for NFMs classified according to the category of metals detected most frequently from fine and coarse fractions, respectively.

The category "Others" includes minor and less common scraps such as bronze, steel-tin cans, Ni scraps and the considerably less common Ag scraps (silverware). All these scraps together represented less than 1.9 wt% of total NFM fraction.

TABLE 4: Categories of potentially marketable NFM scraps.

Category name	Details
Al-scrap	
Al-scrap I	High grade: fraction 10-90 mm and which is mainly composed of UBC and to a lesser extent Al-foils.
Al-scrap II	Low grade: rest of Al scraps.
Cu-scrap	
Cu-scrap I	High grade: the category Cu-wires from the fraction ≥90 mm
Cu-scrap II	Low grade: rest of NFMs, except Zn, Pb and stainless-steel scraps
Pb-scrap	Mixed Pb scrap
Zn-scrap	Mixed Zn scrap
Stainless-steel scrap	Mixed stainless steel scrap

TABLE 5: Prices of nonferrous scrap in Jun 2019.

ISRI code	Category	Price (euro/ton)
SCORE	Zn mixed scrap	600
SABOT	18/8 stainless steel solids	720
RACKS/RADIO	Pb soft scrap	1,100
NA	Pb scrap	1,000
RAINS	Pb scrap from auto batteries	820
BERRY	Dry bright wire	4,000
CANDY	Copper Wire and Tubing Scrap	3,450
DRUID	Insulated Cu wire (85% recovered scrap)	1,900
BIRCH	Copper wire N°2 with a metal purity > 96%	3,250
ZEBRA	Mixed brass	2,400
NA	Heavy brass	2,400
ZORBA	Zorba90 (90% of NFMs)	500
DROID	Insulated copper wire N°2 with a metal purity > 96% (45% recovered scrap)	1,100
TAKE, TALC, TALCRED	UBC	1,400
TAINT/TABOR	Aluminium foil	200

Source: www.recycling.com; www.scrapmonster.com

Cu and Al scraps represented approx. 80% of NFMs recovered from this landfill. Al scraps, mainly present as foils and packaging, were the most common metals found in the fine fraction (44.5 wt%) followed by Cu scraps (Brass and Cu-wires) (33.4 wt%). In the coarse fraction, Cu scraps were the most widely detected NFMs with 50.2 wt%.

Pb and Zn scraps were mainly detected in fine fractions; Pb scraps originate from a series of sources, including automotive battery parts, old plumbing, and roof covers, among other unknown sources, whilst Zn is mainly used as anticorrosive layers in Fe scraps and as an alloy in Cu. However, Zn scraps within NFMs were also found frequently as mechanical components or in alkaline batteries.

Stainless steel scraps were recovered largely from the coarse fraction by hand-sorting, whilst ECSs retrieved only small amounts in the fine fraction. The fine fraction may however contain more stainless steel than the quantities retrieved. The lift-off for stainless steel in ECSs is the lowest of all NFMs (76 times lower than Al), with small pieces tending to remain in the waste when impurities have adhered to the scraps (AbdAlla et al., 2019; Kristian Kahle, Ramboll et al., 2015; Spencer and Schlömann, 1975).

3.2 Thermal processing

Figures 5 and 6 summarise the results obtained from the thermal processing and chemical analysis of each metal sample.

TABLE 6: Mass distribution of LFW processed with ballistic separators.

Screening results [wt%]	Input material	Ferrous (2.39 wt% input)	Non-ferrous (0.47 wt% input)
≥200 mm	6 %	8 %	8 %
200-90 mm	16 %	24 %	18 %
< 90 mm	78 %	68 %	74 %

In general, the fine fractions contained more impurities than coarse fractions (Figure 7). Large metallic particles, largely from the category of C&D waste, did not contain more than 15 wt% of defilements (see all categories in Figure. 5b, with the exception of Al-foils and Al-pack). The only exception was Cu-wires, for which polymeric insulating cover accounted for almost 50 wt%.

With the exception of categories Al-foils, Al-pack and other metals which contained degraded biological matter, the remaining burnable defilements were mostly polymers and carton used in association with various metals.

The chemical compositions presented in Figures 6a and 6b reveal how the two main fractions analysed (< 90mm and ≥90 mm) displayed similar ratios of defilements (circa 30 wt%). In contrast, the proportion of NFMs differed, with Al representing the most widely present traditional metal in the fine fraction, followed by e.g. Cu and Zn, both of which commonly found in MSW (Morf et al., 2013).

Contrary to expectations, the typical chemical composition of scraps from the coarse fraction (originating largely from C&D waste) was dominated by Cu (34.1 wt%), followed by Al (15.6 wt%), rather than vice versa. The important chemical elements Fe, Ni and Cr were also detected due to the presence of stainless steel.

3.3 Assessing the marketability of NFMs

Assessment of the marketability of scraps based on the results obtained by mechanical separation may lead to an inaccurate conclusion as to the potential profitability of these recovered metals. One clear example is represented by Cu. In the coarse fraction, the most frequently detected scrap was Cu-wires (39.2 wt%) (see Cu-wires in Figure 3b). However, when applied to this category, thermal treatment revealed a metal concentration of only 47.8 wt% (see Cu-wires in Figure 5b), thus indicating a lower concentration of actual Cu in the coarse fraction.

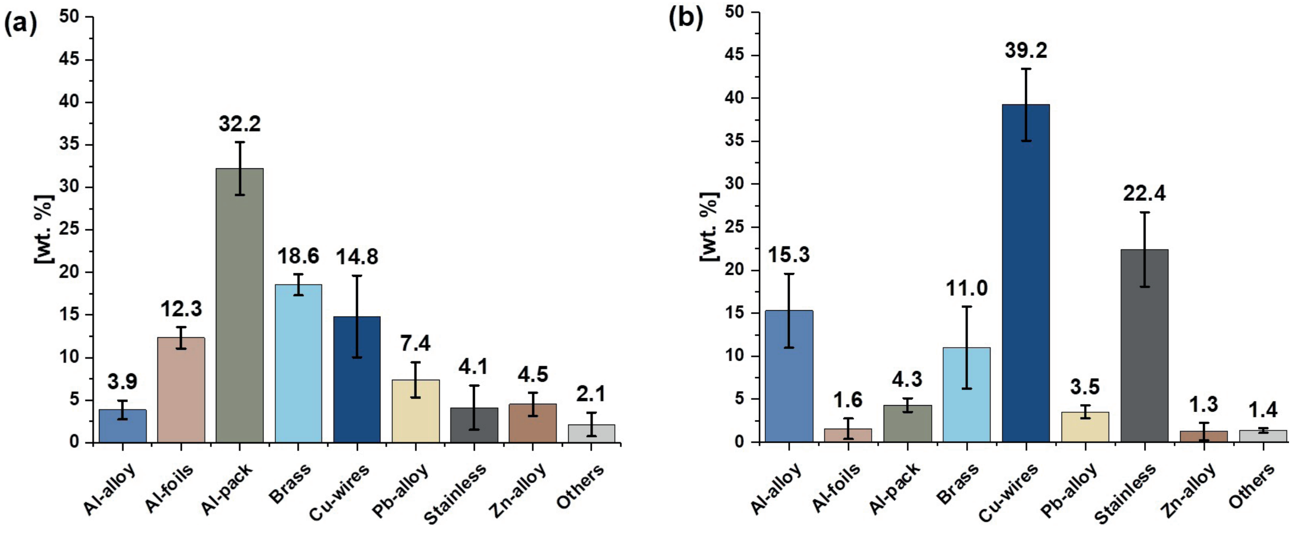

FIGURE 4: Categories of NFMs after mechanical separation [wt%]: (a) fine fractions (<90 mm), (b) coarse fractions (≥90 mm).

3.3.1 Metal concentration and surface defilements

To focus on the first question asked at the start of this paper, relating to metal concentration and surface defilements in NFMs, the results obtained by thermal treatment indicated the presence of approx. 27.3 wt% defilements (Figure 6c), of which 20.8 wt% organic (burnable) and 6.5 wt% inorganic. Both fine and coarse fractions displayed similar trends of defilements (see Figures 6a and 6b). Nevertheless, defilements in fine sub-fractions (4.5-10 mm .10-30 mm and 30-90 mm) showed significant discrepancies, in particular the fraction 4.5-10 mm with impurities amounting to approx. 40-50 wt% (Figure 7).

The origin of these impurities however varied. Defilements in the fine fraction were related to landfilled MSW in which polymers present in packaging and decomposed organic matter in contact with soil material had become bound to the metals over the years.

On the other hand, in the coarse fraction, organics were represented mainly by polymers which had formed composites with metals such as Cu-wires, with a polymeric fraction of roughly 41 wt%. Residual soil materials agglomerated on the metal surface represented the main source of inorganic defilements. Glass and ceramics used in electrical applications, such as switches, fusible plugs, and light bulb holders, among other materials, were detected bound to several metals.

The concentration of metals ranged from 56.5 wt% in the fraction 4.5-10 mm to 74.1 in the fractions ≥90 mm (Figure 7). The fraction 30-90 mm yielded the highest number of metals, driven by Al packaging such as UBC, Al foils and different types of Cu alloys.

3.3.2 Marketable scraps

To answer the last question raised, relating to the commercialisation of the scraps identified, two approaches were used in order to assist decision-makers during the

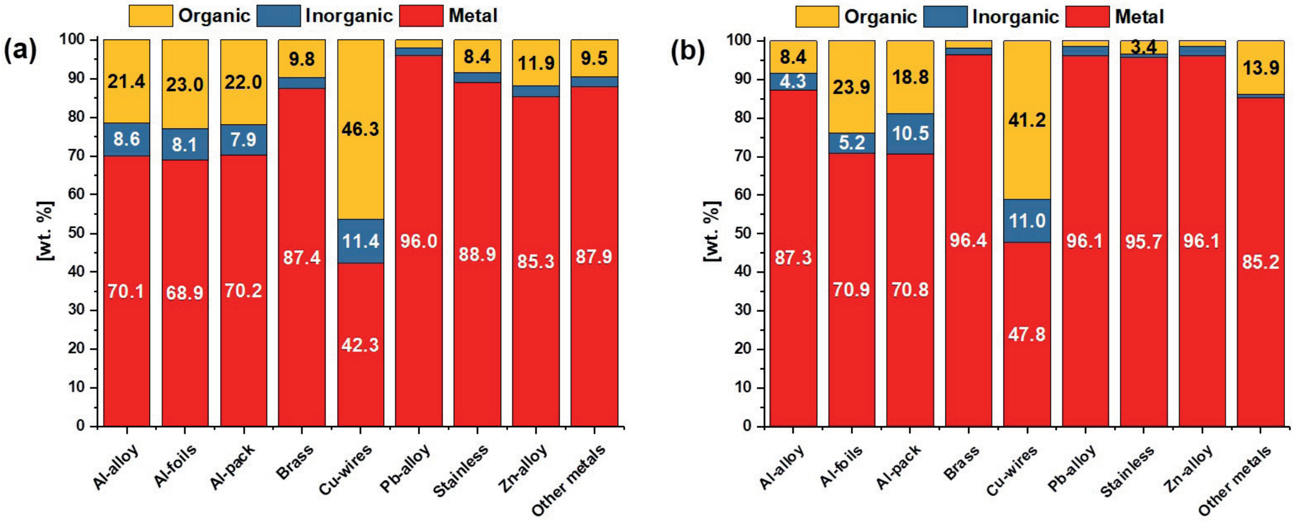

FIGURE 5: Concentration of metal, organic and inorganic matter present in each NFM [wt%]: (a) fine fractions (<90 mm), (b) coarse fractions (≥90 mm).

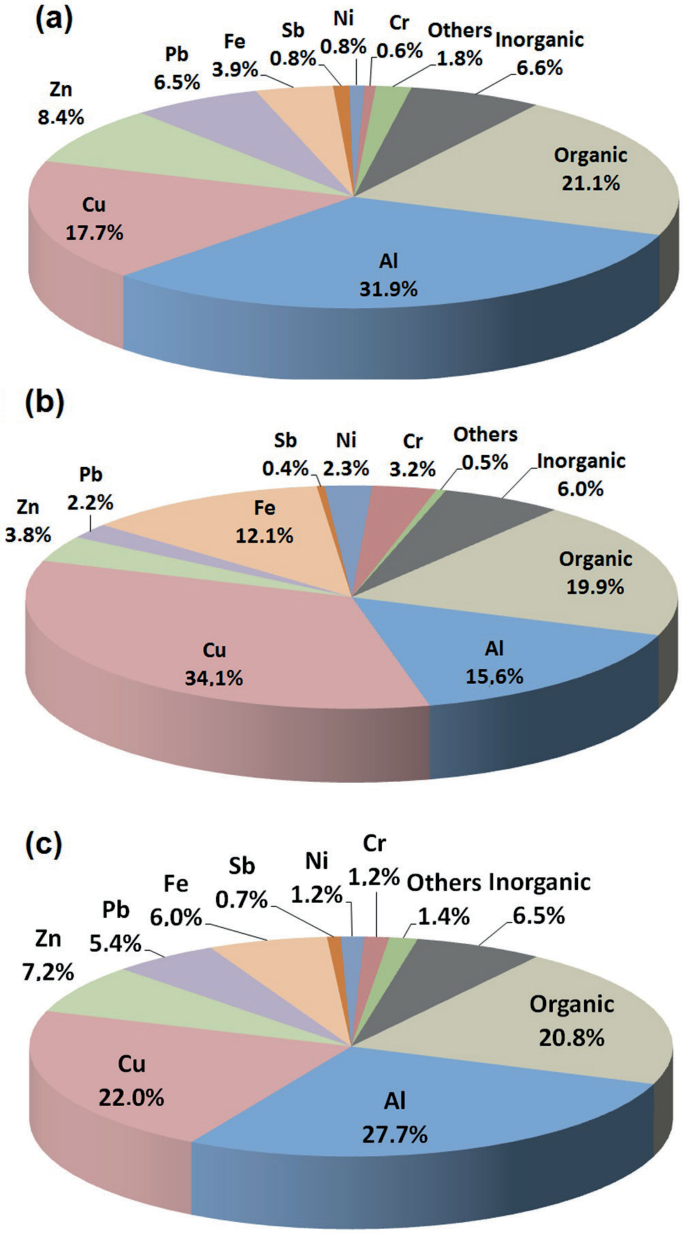

FIGURE 6: Chemical composition of NFMs: (a) fine fractions (<90 mm), (b) coarse fractions (≥90 mm), and (c) global composition.

assessment of upcoming LFM projects.

During the excavation and treatment of LFW in situ, magnetic separators and ECSs may be installed for use in metal separation. On applying these technologies, the extracted NFMs would then be suitable for marketing as a mixed nonferrous scrap. In the presence of Al as the majority metal contained in NFMs, as was the case in the present study, NFMs are traded under the standard identified as Zorba (Scrap Specifications Circular, 2017). This scrap category also requires the addition of two numbers affirming metal concentration.

The price of Zorba90 (90 refers to 90% metal concentration), typically detected in C&D and MSW, is in the range of 500 euros per ton (Table 5). Within the framework of the analysis carried out here, NFMs from MSG was defined as Zorba70, where 70 is an approximate representation of the metal concentration found in this study. Under these terms, NFMs from MSG are routinely marketed for no more than 400 euros per ton.

Whether it is the company carrying out the LFM project or a specialised recycling company to deal with the NFMs is of little concern, the different fractions can still be separated and valorised and the sum remunerated may at times even increase two or three-fold. Under this optimistic approach, Figure 8a, 8b and 9 summarise the results of the seven marketable scraps in terms of proportion detected, contribution of each fraction (<90 mm and ≥90 mm) and metal concentration, respectively.

Al scrap

As stated previously, Al is the most commonly detected NFM, with Al pieces frequently containing Mg, Mn, Si, Fe,

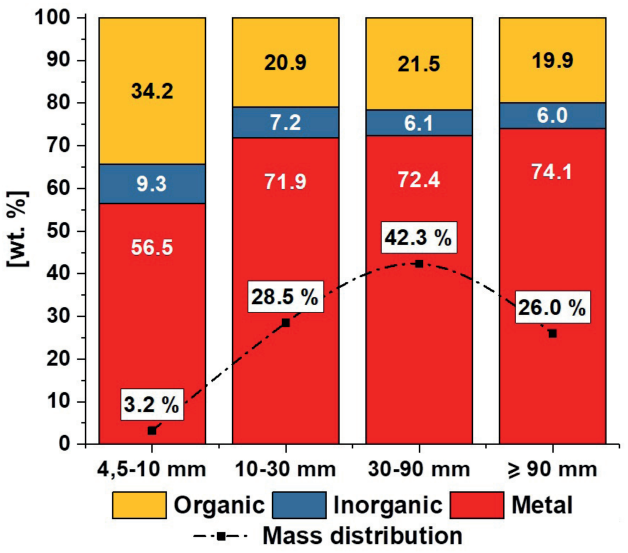

FIGURE 7: Concentration of metal and defilements in NFMs according to particle size [wt%].

and Cu as alloying. The type and amount of alloying in the metal composition is related to the origin of the scraps. Al scraps in the fraction <90 mm originate largely from packaging and foils, in which the metals have a negligible alloying content. On the other hand, the coarse fraction (≥90 mm) contains particles of Al with a wide range of alloying and metallic pieces such as mechanically assembled screws. The characterisation assay performed revealed that the coarse fraction also contained a small proportion of Al packaging and foils. It is important to highlight that Al foils in the coarse fraction were found bound to other materials which had initially been absent. Al packaging detected in the coarse fractions was seven to eight-fold lower than in the fines (see the category Al-pack in Figures 4a and 4b).

As shown in Figure 7, the fraction 4.5-10 mm contained the most significant number of impurities; accordingly, Al was retrieved together with other metals such as Zn, Pb or Cu. The fractions 10-30 mm and 30-90 were made up largely of Al packaging and foils. During thermal treatment, defilements were removed almost entirely; these two fractions therefore are expected to produce a relatively high-grade aluminium during refining.

Although no studies have been conducted to date to investigate the obtaining of Al from LFW, experience gained with MSW indicates the possibility of using dense media separators and XRT sorting technology to separate Al from other NFMs (Capuzzi and Timelli, 2018; Lucas et al., 2019; Schmitz et al., 2006).

Irrespective of whether or not the <10 mm and >90/100 mm fractions are separated by screening, a scrap similar to UBC may be produced from the total fraction of Al scrap (see Figure 8b). UBC scrap is traded as TAKE, TALC or TALCRED (Scrap Specifications Circular, 2017); in Europe, the going rate on the scrap market is up to 1,400 euros per ton (Table 5). These potentially high-grade Al scraps from LFW, known as Al-scrap I, represent 26.4 wt% of NFMs (Figure 7a) and, as shown in Figure 8b, are made up almost totally of Al from the fine fraction (<90 mm). In line with the results presented in Figure 9, 70.7 wt% of this scrap can be valorised, with the potential price of Al-scrap I with defilements being in the range of 990 euros per ton.

On the scrap market, the price for Al foils may reach up to 200 euros per ton (see TAINT/TABOR standard in Table 5), particularly as these foils are highly sensitive to oxidation during refining. According to Soo et al. (2019), the price of Al with high Fe content is 1,000 euros per ton. The category Al-scrap II contains Al from the fraction below 10 mm (mainly Al foils mixed with other metals) and Al from the coarse fraction (Al alloys and Al with mechanically linked metals such as screws and nuts). Consequently, on considering the concentration of impurities (28 wt%), the expected prices would drop to less than 500 euros per ton.

Al scraps are treated exclusively in the secondary production circuit (Bever, 1976) and, due to the presence of undesirable alloying elements in the scrap, are used in combination with primary Al to produce alloys for specific applications, for example, parts and engines for the car industry (Paraskevas et al., 2015).

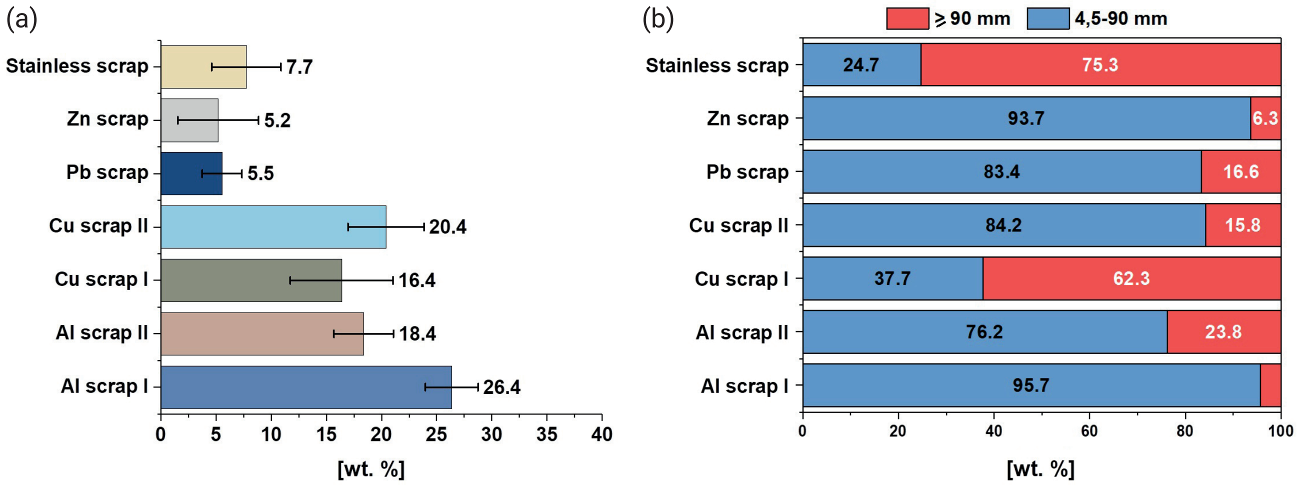

FIGURE 8: Type of marketable NFM scraps: (a) proportions (b) contribution of each fraction.

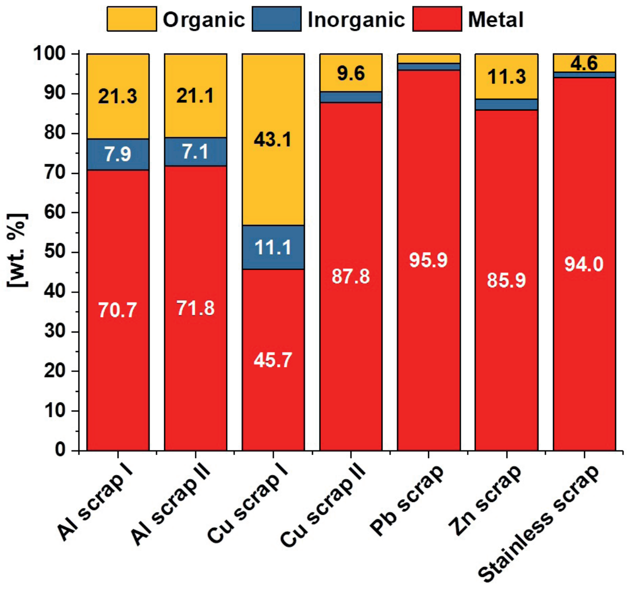

FIGURE 9: Concentration of metal and defilements in marketable NFMs [wt%].

Cu scrap

Cu scraps are the second most common type of NFM detected in the investigated fractions. The amount of Cu found was higher than expected due to the presence of C&D and industrial waste. Two different Cu scraps complying to a large extent with market standards were identified; Cu-scrap I obtained entirely from the category Cu-wires, and Cu-scrap II containing metals from the categories Brass and Other metals. Sorting technologies or dense-media separators may be used to separate wires from other Cu scraps. Almost 55 wt% of Cu wires are non-metallic (Fig. ure 8), therefore featuring a low relative density compared to other heavy NFMs (lead, zinc, stainless steel and brass).

The purity of Cu in wires usually exceeds 96% and can be sold on the scrap market in the Droid category (Insulated Cu wire scrap N°2). The standard applied for Droid normally stipulates a metal concentration of 45%, similar to the trends observed in this study (Figure 9); rates currently offered per ton are in the range of 1,100 euros (see Table 5). Providing a chopping process (Schlesinger et al., 2011) is carried out, the metal obtained may reach prices of 3,250 euros per ton under the Birch standard.

Cu-scrap II contains 63 wt% of Cu, in addition to a series of other alloying materials and impurities such as Zn, Pb, Ni, Sn, Fe, Ag and Zn, with its alloys also being included in this category. This topic will be discussed further below in “Zn and Pb scrap”. Accordingly, Cu-scrap II, consisting of a mixture of heavy NFMs, reaches requirements for the standard Zebra or Heavy brass (Table 5). This category features only 12. wt% defilements (Figure 9) and is marketed at 2,400 euros per ton.

Indeed, Cu-scrap I is valorised by undergoing a chopping process in either the primary or secondary Cu production circuit during the first or second refining stage to produce “Anode-copper”. Potential applications for Cu-scrap II include use in a matte smelter or converter furnaces, which use scraps having a Cu concentration of less than 80% (Habashi, 1998; Schlesinger et al., 2011).

Pb and Zn scrap

Pb-scrap represents approx. 5.5 wt% of all NFMs identified (Figure 8a) and, as shown in Figure 8b, is found mainly in the fraction <90 mm. Analysed Pb pieces featured the presence of less than 5% defilements (Figure 9), indicating the suitability of these scraps for direct marketing as “mixed Pb scrap” or “Pb scrap” (Table 5). The current rate for Pb scrap, separated from NFMs by means of sorting technologies, is up to 1,000 euros per ton.

The scraps undergo treatment in the secondary Pb industry initially via pyrometallurgical treatment and subsequently electro-refining in the same way as Cu (Habashi, 1998).

Zn-scrap is tradable as Score (Scrap Specifications Circular, 2017) with a marked price of 600 euros per ton. However, only Zn scraps from the coarse fraction can potentially be separated using sorting technologies in view of the relatively high purity. The recovery of Zn from fine fractions is complex, being frequently bound to other metals and polymers. Cu-scrap II contains Zn as the main alloy, and during the refining of Cu, Zn oxide is recovered from the off-gas of converter furnaces. The latter might therefore also be included as Cu-scrap II.

Old stainless steel scrap

Approximately 75% of stainless steel scraps originating largely from C&D or industrial waste were recovered from the coarse fraction. In terms of chemical composition, more than 85 wt% of the stainless steel recovered was AISI 304 or 316 (austenitic stainless steel). The steel industry is extremely severe with regard to the nature of pre-existing alloying elements in these scraps, indicating the need to apply sorting technologies to separate the scraps into different stainless steel categories. On separation from other NFMs, austenitic scrap is traded under the ISRI code Sabot (Scrap Specifications Circular, 2017), with a market price of 720 euros per ton (Table 5).

Table 7 summarises calculation of the feasible price ranges for all NFMs, including defilements.

4. DISCUSSION

Prior to the advent of thermal treatment, separation (i.e. cleaning) of organic matter and soil from the surface of the metal was an arduous task. The majority of the metals had been buried, pressed and compacted under the weight of overlying waste for a period of 40 to 60 years. During this time, defilements had frequently become strongly bound to the metals. Accordingly, when assessing the quality of metal retrieved from landfills, studies conducted to investigate the effect generated during anaerobic and humic phases (Belevi and Baccini, 1989; Bozkurt, 1998; Bozkurt et al., 1999; Martensson et al., 1999) should be given due consideration. During the anaerobic phase, metals are affected by corrosion due to the presence of organic acids. The anaerobic phase is followed by slow mineralisation of organic matter, which might explain the difficulties encountered when cleaning the metals.

TABLE 7: Calculated potential prices of NFMs recovered from MSG.

Category	Proportion [wt%]	Potential Price [euro/ton]	ISRI code	Details
Realistic approach				
NFM	100	400	Zorba70	Mixed nonferrous scrap with a metal concentration of 70%
Total	400 euros per ton			
Optimistic approach				
Al-scrap				
Al-scrap I	26.4	900	TAKE, TALC or TALCRED	UBC with a small amount of Al-foils
Al-scrap II	18.4	500	NA	Mixture of Al-foils priced at 200 euros per ton and Al polluted with Fe scrap with a price of 1000 euros per ton (Soo et al. (2019)
Cu-scrap				
Cu-scrap I	16.4	1,100	Droid	Insulated Cu wire scrap N°2 (metal purity >96 %)
Cu-scrap II	20.4	2,400	Zebra	Mixed heavy nonferrous metals
Pb-scrap	5.5	1,000	NA	mixed lead scrap does not have an ISRI code, but is commercialised as is.
Zn-scrap	5.2	600	Score	Zn scrap from the coarse fractions
Stainless steel scrap	7.7	720	Sabot	Austenitic stainless steel scraps
Total	1,141.24 euros per ton			

In spite of a large number of surface defilements attached to these scraps, the majority of NFMs show no severe signs of deterioration compared with ferrous scraps, not included in this study. Nevertheless, some Cu alloys and all steel-tin cans analysed showed clear signs of deterioration.

The use of mobile technology is mandatory in the context of LFM projects in order to process LFW in situ. For this purpose, magnetic separators and ECSs are used in combination with other equipment such as ballistic separators and shredders to extract metals and other materials.

The use of more sophisticated in-situ technologies to separate scraps into different types should be evaluated in terms of cost and potential benefits to be obtained. Realistically however, in an LFM project, "mixed nonferrous scrap" alone is retrieved and traded direct from the landfill.

An intermediate approach aimed at separating NFMs into a light fraction (composed mostly of aluminium) and a heavy fraction employing dense media separators in situ may also be conceivable. Should this be the case, the prices paid will be intermediate, ranging from 500 to 700 euros per ton.

5. CONCLUSIONS

Preliminary results obtained by means of mechanical and manual processing revealed a concentration of NFMs corresponding to 4.8 kg per ton of LFW. Defilements however amounted to 27.3 wt%, thus, the actual amount of recoverable NFMs wass closer to 3.5 kg per ton.

Application of a thermal process following the guidelines issued by the Al industry for de-coating treatments proved useful in eliminating and separating the majority of defilements from NFMs in a raw state. It should however be highlighted that prior to incineration metal scraps should be separated according to metal categories, e.g. Al, Cu, Pb, Zn and stainless steel.

The steel and Al industries are extremely severe in relation to the pollutants and alloying content of scraps. Accordingly, these two metals will need to be subjected to particular care in separation and assessment; the use of sorting technologies such as those based on XRF and XRT sensors is recommended.

The Cu industry is marginally flexible with regard to the type of defilements and metals mixed with Cu scraps in view of the possibility of their re-use in a wide range of processes in both primary and secondary circuits. Primary production circuits apply stricter limitations for pollutants and alloying content, dependent on whether these scraps enter into the first or second refining steps; however, less severe constraints are applied if the scraps are used in matte smelters.

The current rates paid in the commercialisation of NFMs may vary from 400 euros for a mixed-nonferrous scrap to more than 1,100 euros per ton for NFMs that have been separated and divided by categories and grades. To conclude therefore, appropriate technical and economic assessment should be undertaken with the aim of determining the most suitable strategy in order to maximise profitability of the recovered scraps.

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10 MONT-SAINT-GUIBERT CASE STUDY: CHARACTERIZATION AND VALORIZATION POTENTIAL OF RECOVERED COMBUSTIBLES AND INERT FRACTIONS FROM THE FINE FRACTIONS

Scientific article no. 9: "Case Study on Enhanced Landfill Mining at Mont-Saint-Guibert Landfill in Belgium: Physico-Chemical Characterization and Valorization Potential of Combustibles and Inert Fractions Recovered from Fine Fractions"

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Annotation on my personal contribution to this scientific article:

I conceived the plan for the laboratory analysis in consultation with Daniel Vollprecht and Roland Pomberger. The samples were prepared by me, as well as most of the article. The results of the laboratory analysis and their interpretation were performed in collaboration with Daniel Vollprecht, who also was involved in the review and revision of the article. All authors reviewed the whole article.

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CASE STUDY ON ENHANCED LANDFILL MINING AT MONT-SAINT-GUIBERT LANDFILL IN BELGIUM: PHYSICO-CHEMICAL CHARACTERIZATION AND VALORIZATION POTENTIAL OF COMBUSTIBLES AND INERT FRACTIONS RECOVERED FROM FINE FRACTIONS

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ABSTRACT

The fine fractions account for the largest share of material recovered through (enhanced) landfill mining. These fractions typically present challenging characteristics for processing and valorization methods and, hence, they have been largely discarded in previous landfill mining projects. This situation has hindered the economic and environmental feasibility of landfill mining, since most of the excavated waste has been directed back into the landfill. Therefore, the fine fractions are one of the major challenges faced by (enhanced) landfill mining and suitable material and energy recovery schemes for these fractions need to be further developed and, if necessary, created. To this end, the physico-chemical characteristics of the "Combustibles" and "Inert" fractions recovered from the fine fractions <90 mm through a dry-mechanical process have been determined and their suitability for waste-to-material and waste-to-energy schemes has been evaluated in the MSG case study. The recovered "Combustibles" fractions represented 12.5 wt.% and 9.0 wt.% of the fine fractions <90 mm processed in the optimal water content and dry states, while the recovered "Inert" fractions accounted for 35.5 wt.% and 37.2 wt.%, respectively. According to the EN 15359:2011, the "Combustibles" fractions could be valorized as SRF in (co-)incineration, power and cement plants in both the optimal water content state and the dry state in the EU. However, in Austria these fractions can only be incinerated and not co-incinerated according to the Austrian Waste Incineration Ordinance (AVV), since in some cases they present concentrations of As, Cd, Co, Hg and Pb above the limit values. Therefore, in contrast to conventional (co-)incineration, the plasma gasification process proposed by the NEW-MINE project might offer a potential waste-to-energy valorization route for the combustible fractions obtained from the fine fractions of landfill-mined waste. As for the "Inert" fractions, there is no overarching legislation in the EU to regulate such materials yet in place and, hence, these fractions are solely subject to national or local regulations on recycling building materials. In Austria the "Inert" fractions would need further treatment in order to be valorized as a substitute for construction aggregates according to the Austrian Recycling Building Materials Ordinance (RBV), as they exceed the limit values for hydrocarbons, Cd, Pb, Zn, NH_4^+ and anionic surfactants in certain cases. Therefore, suitable waste-to-material valorization schemes for the recovered inert fractions from the fine fractions of landfill-mined waste are to be further developed, while appropriate overarching regulations need to be created at EU level.

1. INTRODUCTION

In many cases landfill mining (LFM) has failed as a business model and it has mainly been carried out within the framework of contaminated sites remediation to address the threat that landfills and dumpsites pose to the health and well-being of the environment. However, the development of novel technologies is aiming to eventually bridge the gap between the practically possible and the economically feasible, and might gradually enable further material and energy recovery from landfill-mined material,

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as well as facilitate its integration into current waste management systems (Hernández Parrodi et al., 2019b). For this purpose, suitable valorization routes for the outputs of LFM need to be further developed and, if necessary, created. For example, in the case of the recovered combustible fractions some projects have investigated their traditional co-incineration in cement plants (Wolfsberger et al., 2015), whereas others have aimed for non-coventional routes of energy recovery through alternative thermo-chemical processes, such as pyrolysis and gasification, which might allow the upcycling of their residues into higher value glass-ceramics (Monich, Romero, Höllen, & Bernardo, 2018; Rabelo Monich, Vollprecht, & Bernardo, 2020) and inorganic polymer binders (Ascensão, Marchi, Segata, Faleschini, & Pontikes, 2019; Machiels et al., 2017). The latter approach is addressed in the enhanced landfill mining (ELFM) concept, which has been put to test in a case study at the Mont-Saint-Guibert (MSG) landfill site in Belgium. The MSG landfill case study is being carried out within the framework of the EU Training Network for Resource Recovery through Enhanced Landfill Mining - NEW-MINE. As defined by Jones et al., 2013, ELFM is the safe conditioning, excavation and integrated valorization of historic and/or future landfilled waste streams as both materials (Waste-to-Material (WtM)) and energy (Waste-to-Energy (WtE)), using innovative transformation technologies and respecting the most stringent social and ecological criteria.

One of the main challenges in (E)LFM are the fine fractions, since they present difficult characteristics for their processing and valorization, and can account for 40-80 wt.% of the total amount of landfill-mined waste (Hernández Parrodi, Höllen, & Pomberger, 2018a). The fine fractions have been frequently defined as the material with a particle size <60 mm to <10 mm in previous (E)LFM studies (Hernández Parrodi et al., 2018a); however, there is no convention in that regard to date. Furthermore, one commonly chosen alternative in prior projects has been to classify the fine fractions as a residual fraction and direct them back into the landfill (Bhatnagar et al., 2017; Kaartinen, Sormunen, & Rintala, 2013; Münnich, Fricke, Wanka, & Zeiner, 2013), which has had a critical impact on the economic and environmental feasibility of LFM projects. Therefore, the recovery of material and energy from the fine fractions has been included into the scope of the MSG case study. To this end a mechanical processing approach was designed and applied to the fine fractions in the optimal water content (owc) and dry states, according to the results of the material characterization of the fine fractions reported by Hernández Parrodi et al., 2019a and the strategies for WtM and WtE proposed in Hernández Parrodi, Höllen, & Pomberger, 2018b. In the MSG case study the fine fractions are the material with a particle size <90 mm and the owc state corresponds to a water content of around 15 wt.%. The owc state aims at minimizing material losses in the form of dust and small particle-sized and light materials, as well as decreasing the amount of energy required in the drying process. In addition, the owc should not compromise the effectivity and efficiency of a dry-mechanical processing approach. Hence, the mechanical processing approach of the MSG case study was tested in both the owc and dry states, in order to study and evaluate the effects of the owc in terms of the processability of the fine fractions <90 mm and the quality of the produced material fractions. The tested approach consisted of a series of mechanical processing steps, which classified the fine fractions <90 mm into different material fractions and particle size ranges according to their physical properties, such as particle size, shape and density, among others, in order to enable material and energy recovery. The mechanical processing produced the following material fractions: “Fine fractions <4.5 mm”, “Combustibles”, “Inert”, “Ferrous metals” and “Non-ferrous metals”. Further details on the employed mechanical processing and produced fractions are reported by Hernández Parrodi, Raulf, Vollprecht, Pretz, & Pomberger, 2019c. The “Fine fractions <4.5 mm” were further mechanically processed and investigated by Vollprecht, Hernández Parrodi, Lucas, & Pomberger, 2020, while the quality of the extracted “Non-ferrous metals” was studied in Lucas et al., 2019. The recovery of ferrous metals from landfilled material has been successfully carried out in previous investigations (Van Vossen & Prent, 2011; Wagner & Raymond, 2015) and, therefore, the “Ferrous metals” fraction was not further investigated in the MSG case study. Sieving the excavated landfill material into different particle size ranges as a first treatment step, followed by sorting the coarse fractions into different waste types to characterize the material has been addressed in several previous (E)LFM investigations (Garcia Lopez et al., 2019; Hogland, 2002; Hull, Krogmann, & Strom, 2005; Kurian, Esakku, Palanivelu, & Selvam, 2003; Quaghebeur et al., 2013; Stessel & Murphy).

The present study focuses on the obtained “Combustibles” and “Inert” fractions, which are intended to be valorized as an alternative fuel (i.e. refuse derived fuel (RDF)) and a substitute for construction aggregates (e.g. construction gravel), respectively. The main physico-chemical characteristics of each fraction, according to the applicable European Directives (i.e. 2000/76/EC on Incineration of Waste, EN 15359:2011 on Solid Recovered Fuels, 2008/98/EC on Waste and 1999/31/EC on Landfill of Waste) and Austrian ordinances (i.e. Waste Incineration Ordinance (Abfallverbrennungsverordnung – AVV) and Recycling Building Materials Ordinance (Recycling-Baustoffverordnung – RBV)), were determined in the owc and dry states. That information was used to evaluate the quality of the produced fractions in each state and determine their suitability for the intended WtM and WtE valorization routes, as well as to analyze the effects of the owc on the quality of each fraction.

2. MATERIALS AND METHODS

2.1 Site description, excavation works and mechanical pre-processing

The present case study was carried out at the landfill site “Centre d´enfouissement Technique de Mont-Saint-Guibert (CETeM)”, which is located in the municipality of MSG, Belgium. This landfill served as one of the main disposal sites of municipal solid waste, non-hazardous industrial waste and construction and demolition waste in the province of Walloon Brabant (Bureau d´études greisch (beg), 2002). The landfilled material was extracted by means of excavators and pre-processed with a ballistic separator (Stadler model STT 6000) directly after excavation. The ballistic separation was performed in two steps: firstly with screen paddles of 200 mm and secondly of 90 mm, from which representative samples were taken for further study. The fine fractions <90 mm of this case study were obtained from the second ballistic separation step and represented around 77 wt.% of the total amount of pre-processed material (~374 Mg). More detailed information about the landfill site, excavation works, mechanical pre-processing, sampling procedures and characteristics of the excavated material can be found in Garcia Lopez et al., 2019 and Hernández Parrodi et al., 2019a.

2.2 Mechanical processing of the Combustibles and Inert fractions

The “Combustibles” and “Inert” fractions were produced with the light and heavy fractions, respectively, which in turn were obtained from the density separation steps of the mechanical processing in the owc and dry states in Hernández Parrodi et al., 2019c. Previous to the density separation steps, the fine fractions <90 mm were subjected to particle size classification and ferrous and non-ferrous metals extraction. The particle size classification steps produced the particle size ranges 90-30 mm, 30-10 mm and 10-4.5 mm. The density separation method applied to those particle size ranges corresponds to windsifting. A cross-flow windsifter was employed in the particle size range 90-30 mm, whereas a zig-zag windsifter was used in the particle size ranges 30-10 mm and 10-4.5 mm. After density separation, both light and heavy fractions were sieved at 4.5 mm in order to remove loosened fine particles (i.e. impurities) throughout the mechanical processing. Subsequently, the heavy fractions were processed with near infrared (NIR) sorting to further extract combustible materials. The extracted combustible materials from the heavy fractions were added to the light fractions for joint valorization and to produce the “Combustibles” fraction. The heavy fractions after further removal of combustible materials were denominated the “Inert” fractions. Further information on the application of NIR sorting to the heavy fractions of the fine fractions <90 mm are reported in Küppers, Hernández Parrodi, Garcia Lopez, Pomberger, & Vollprecht, 2019 and Hernández Parrodi et al., 2019c.

The median values obtained from processing all composite samples of the fine fractions <90 mm (n=16) in the owc (n=8) and dry (n=8) states were used to elaborate the general mass balance of the mechanical processing, which was reported and analyzed in Hernández Parrodi et al., 2019c.

2.2.1 Combustibles fractions

The general mass balance of the mechanical processing of the fine fractions <90 mm in Hernández Parrodi et al., 2019c reported total amounts of “Combustibles” of 12.5 wt.% in the owc state and 9.0 wt.% in the dry state. In turn, the mass distribution of the “Combustibles” fraction among the particle size ranges 90-30 mm, 30-0 mm and 10-4.5 mm in the owc state was about 4.6 wt.%, 5.0 wt.% and 2.5 wt.%, respectively. In the dry state, the particle size range 90-30 mm presented an amount of 4.1 wt.%, while 30-10 mm accounted for 2.7 wt.% and 10-4.5 mm for 2.0 wt.%. This information is shown as Sankey diagrams in Figure 1.

The physical appearance of each of the particle size ranges of the produced “Combustibles” fractions by the employed mechanical processing in the owc and dry states is displayed in Figure 2. In those images it can bee seen that the “Combustibles” fractions were mainly composed of plastics, textiles, wood and paper & cardboard in both states, as well as that the presence of plastics and textiles seems to decrease with particle size. It is also clear that the owc state presents a higher amount of surface defilements (i.e. impurities) than the dry state. Composite samples of each of these fractions were used for the laboratory analyses performed in this study.

2.2.2 Inert fractions

As shown in Figure 3, the “Inert” fractions accounted for 35.5 wt.% of the total amount of produced fractions in the owc state; from which 15.3 wt.%, 15.6 wt.% and 6.3 wt.% corresponded to the particle size ranges 90-30 mm, 30-10 mm and 10-4.5 mm, respectively. In turn, the dry state showed a total amount of 37.2 wt.%, with 15.5 wt.% of the material present in the particle size range 90-30 mm, 13.0 wt.% in 30-10 mm and 8.1 wt.% in 10-4.5 mm.

Figure 4 displays photograps of the “Inert” fractions in the owc and dry states, in which it can be observed that these fractions are mostly comprised of concrete, bricks, stones and glass. The presence of concrete and bricks appears to decrease with particle size in both states. Similarly as for the “Combustibles” fractions, the “Inert” fractions show a greater amount of impurities in the owc state than in the dry state. Composite samples were used to deter-

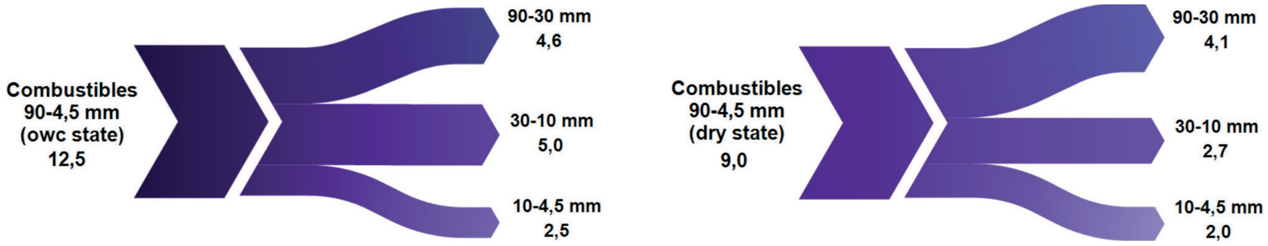

FIGURE 1: Mass distribution of the “Combustibles” fractions among particle size ranges in the owc and dry states [figures in wt.%] (Hernández Parrodi et al. 2019c).

FIGURE 2: "Combustibles" fractions in the owc and dry states (Hernández Parrodi et al. 2019c).

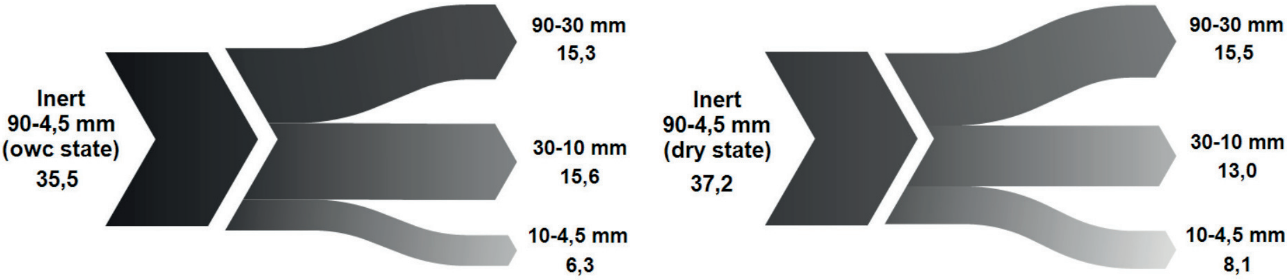

FIGURE 3: Mass distribution of the "Inert" fractions among particle size ranges in the owc and dry states [figures in wt.%] (Hernández Parrodi et al. 2019c).

mine the physico-chemical properties of these fractions as well.

2.3 Laboratory analyses

The determination of the physico-chemical characteristics of the "Combustibles" and "Inert" fractions was performed by the laboratory for environmental analyses of the Chair of Waste Processing Technology and Waste Management (AVAW) of the Montanuniversität Leoben, which is accredited as testing laboratory according to ISO/IEC 17025.

A total of 3 composite samples (n=3) of each fraction (i.e. "Combustibles" and "Inert" fractions) of each particle size range (i.e. 90-30 mm, 30-10 mm and 10-4.5 mm) and of each state (i.e. owc and dry states) was analyzed in order to determine the pseudo-total contents (aqua regia digestion), among other parameters, of the "Combustibles" and "Inert" fractions. Additionally, the leachable concentrations of the "Inert" fractions were determined, as leaching tests are useful to determine the susceptibility of the fine fractions to serve alternative purposes (Kaczala et al., 2017). Depending on the reference taken for the limit values to be met, the arithmetic mean and standard error, with a confidence interval of 95% (Ci= 95%), or the 50th percentile (median) and 80th percentile of the laboratory results were employed to describe each of the analyzed fractions. Box-and-whisker plots were elaborated with the 20th, 50th and 80th percentiles, as well as with the maximum and minimum values.

2.3.1 Laboratory analyses of the Combustibles fractions

Solid matter laboratory analyses were performed to determine the main physico-chemical characteristics of the "Combustibles" fractions, as well as to individually evaluate their suitability for the production of RDF according to the EN 15359:2011 and the AVV. The results of each particle size range were also employed to calculate the physico-chemical characteristics and quality of the mixture of the 3 particle size ranges, in the original proportions in which they were generated by the mechanical processing, as a single particle size range (i.e. 90-4.5 mm). The original proportions in which the "Combustibles" fractions were generated were determined by ponderating the mass distribution of the owc and dry states presented in Figure 1. In the owc state, the median original proportions were about 38 wt.%, 41 wt.% and 21 wt.% of the particle size ranges 90-

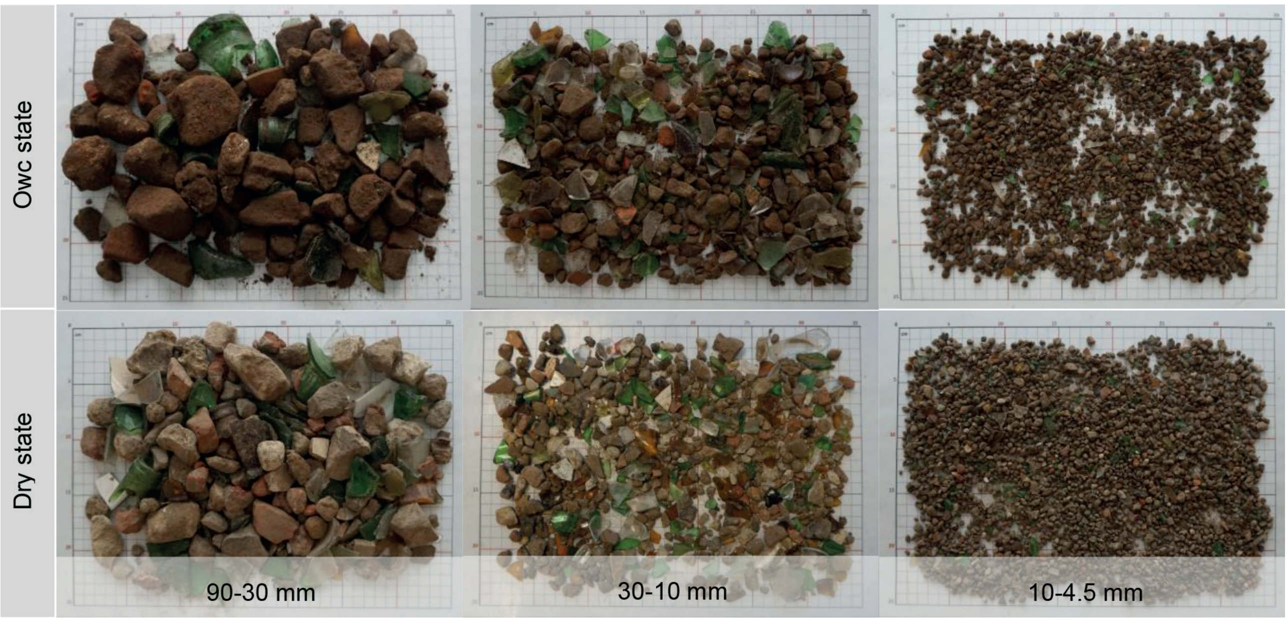

FIGURE 4: "Inert" fractions in the owc and dry states (Hernández Parrodi et al. 2019c).

30 mm, 30-10 mm and 10-4.5 mm, respectively. The median original proportions in the dry state presented amounts of around 47 wt.% for the particle size range 90-30 mm, 31 wt.% for 30-10 mm and 22 wt.% for 10-4.5 mm.

The pseudo-total contents of heavy metals and other elements in the "Combustibles" fractions, as well as of additional parameters (e.g. dry matter (DM) content, net calorific value (NCV) and ash content (AC)), in the owc and dry states were determined according to the European Standard EN 15359:2011 on "Solid Recovered Fuels – Specifications and Classes" and the AVV. In the EU the EN 15359:2011 provides the overarching classification and specifications criteria for the production and utilization of solid recovered fuel (SRF), whereas the Directive on the Incineration of Waste (2000/76/EC) sets the emission limit values for waste (co-)incineration plants. The EN 15359:2011 employs parameters such as NCV, chlorine (Cl) and mercury (Hg) to determine if the material in question can be utilized as SRF and, given that the material meets the specifications, classifies the SRF according to its properties. The classification system of the EN 15359:2011 is shown in Table 1.

In Austria, the production and utilization of RDF (including SRF), as well as the emissions from co-incineration, cement and power plants, are further regulated in the AVV. This ordinance sets the limit values for the contents of certain heavy metals (i.e. arsenic (As), cadmium (Cd), cobalt (Co), chromium (Cr), mercury (Hg), nickel (Ni), lead (Pb) and antimony (Sb)) in RDF depending on the type of application. Table 2 presents a summary of the limit values of the AVV for the corresponding heavy metals according to utilization type.

The determination of the DM content was done according to the DIN EN 14346 (Process A), while the DIN 51900-1 was followed to determine the NCV. The contents of Cl, fluorine (F), sulfur (S) and bromine (Br) were determined via calorimetric digestion (ÖNORM EN 14582) according to the DIN EN ISO 10304-1. The AC was determined following the ÖNORM EN 15403 and the heavy metals pseudo-total contents were determined through inductively coupled plasma - mass spectrometry (ICP-MS) according to the ÖNORM EN 15411. The total organic carbon (TOC) and polycyclic aromatic hydrocarbons (Σ16PAHs/EPA) contents were determined according to the ÖNORM EN 13137 and the ÖNORM L 1200, respectively.

2.3.2 Laboratory analyses of the Inert fractions

Analogously to the "Combustibles" fractions, the particle size ranges 90-30 mm, 30-10 mm and 10-4.5 mm of the "Inert" fractions in the owc and dry states were subject

TABLE 1: Specifications and classes of SRF according to the EN 15359:2011.

Classification property	Statistical measure	Unit	Classes				
			1	2	3	4	5
NCV	Mean	[MJ/kg (ar)]	≥25	≥20	≥15	≥10	≥3
Cl	Mean	[wt.% (DM)]	≤0.2	≤0.6	≤1	≤1.5	≤3
Hg	Median	[mg/MJ (ar)]	≤0.02	≤0.03	≤0.08	≤0.15	≤0.5
	80th percentile	[mg/MJ (ar)]	≤0.04	≤0.06	≤0.16	≤0.3	≤1

Notes: DM= dry matter, ar= as received.

TABLE 2: Limit values for the utilization of RDF according to the AVV.

Parameter	Unit	For use in co-incineration plants		For use in cement plants		For use in power plants 1)	
		Median	80th percentile	Median	80th percentile	Median	80th percentile
As	[mg/MJ (DM)]	1	1.5	2	3	2	3
Cd	[mg/MJ (DM)]	0.17	0.34	0.23	0.46	0.27	0.54
Co	[mg/MJ (DM)]	0.9	1.6	1.5	2.7	1.4	2.5
Cr	[mg/MJ (DM)]	19	28	25	37	31	46
Hg	[mg/MJ (DM)]	0.075	0.15	0.075	0.15	0.075	0.15
Ni	[mg/MJ (DM)]	7	12	10	18	11	19
Pb	[mg/MJ (DM)]	15	27	20	36	23	41
Sb	[mg/MJ (DM)]	7	10	7	10	7	10

Notes: DM= dry matter.

1) With a contribution of ≤10% of the thermal energy from the incineration of waste to the total thermal energy.

to solid matter analyses and, in addition, to leaching tests. The suitability of the "Inert" fractions for the production of a substitute for construction aggregates was evaluated according to the RBV and was performed per particle size range and as a single particle size range mixed in the original proportions in which the particle sizes were generated (only applicable to the solid matter analyses) as well, which were calculated by ponderating the mass distribution of the owc and dry states displayed in Figure 2. In the owc state, the median original proportions of the particle size ranges 90-30 mm, 30-10 mm and 10-4.5 mm corresponded to about 41 wt.%, 42 wt.% and 17 wt.%, whereas in the dry state they accounted for around 42 wt.%, 36 wt.% and 22 wt.%, respectively.

The solid matter analyses and leaching tests were carried out according to the RBV, which establishes the specifications, limit values and quality classes for the reuse and recycling of construction and demolition waste, as well as the allowed applications of such materials in Austria. However, the scope of this ordinance contains an exclusive lists of waste types which may be used for the production of recycled aggregates. Inert materials recovered through (E)LFM are not included in that list. Nevertheless, to this day the EU does not yet have an overarching directive to regulate this type of materials (Saveyn et al., 2014) and, therefore, the RBV was taken as a reference in this study. The RBV employs parameters, such as heavy metals (i.e. As, Cd, Co, Cr, Cu, Hg, Ni, Pb, and Zn), hydrocarbon index (KW index) and Σ16PAHs/EPA content, in the solid matter to determine if the material in question is suitable to replace construction aggregates in certain applications, which are also defined in the same ordinance. As for the leaching tests, that ordinance sets the limit values for parameters such as pH, electric conductivity, TOC, KW index, Co, Cr, Cr, molybdenum (Mo), Ni, ammonium-N (NH_4^+), chloride (Cl^-), nitrite (NO_2^-), sulfate (SO_4^{2-}) and the methylene blue active substance assay (MBAS assay), among others. A synopsis of the classification system of the RBV for both solid matter and leachate analyses is presented in Table 3.The allowed applications of each of the quality classes in Table 3 are defined in the RBV as well, which are shown in Table 4.

Regarding the solid matter analyses, the S content of the "Inert" fractions was determined via inductively coupled plasma - optical emission spectrometry (ICP-OES) according to the ÖNORM EN ISO 11885. The concentrations of the heavy metals and other elements were determined via inductively coupled plasma - mass spectrometry (ICP-MS) and aqua regia digestion (ÖNORM EN 13657 (6.3)) according to the ÖNORM EN ISO 17294-2. For the determination of the KW index the ÖNORM EN 14039 was followed. Loss on ignition (LOI) was determined according to the DIN EN ISO 26845:2008-06 at 1025°C, deviating from the standard as individual determination. The chemical composition was determined through quantitative x-ray fluorescence (XRF) according to the DIN EN ISO 12677. DM, TOC and Σ16PAHs/EPA contents were determined analogously to the "Combustibles" fractions.

As for the leaching tests, pH was determined according to the ISO 10523, while the DIN EN 27888 was used for the determination of the electric conductivity. The concentrations of Cl^-, NO_2^-, SO_4^{2-} and fluoride (F^-) were determined following the DIN EN ISO 10304-1 and NH_4^+ was determined according to the DIN 38406-5. The ÖNORM EN 903 was followed for the MBAS assay, whereas TOC and KW index were determined according to the DIN EN 1484-3 and the EN ISO 9377-2, respectively. The concentrations of Co, Cr, Cr, Mo and Ni were determined via leaching tests (ÖNORM EN 12457-4 (waste)) according to the ÖNORM EN ISO 17294-2 (ICP-MS).

3. RESULTS AND DISCUSSION

3.1 Combustibles fractions

The results of the solid matter laboratory analyses of the "Combustibles" fractions for the parameters NCV, AC, Cl, F, S, Br, C, H, Hg and N, as well as DM, TOC and Σ16PAHs/EPA contents, per particle size range (i.e. 90-30 mm, 30-10 mm, 10-4.5 mm and 90-4.5 mm (mixed in original proportions)) and state (i.e. the owc and dry states) are presented in Table 5.

The figures in Table 5 show that the DM content in the owc state, which was set prior to the experiments to 85.0 wt.%, varied between 86.7 wt.% and 74.5 wt.% among the particle size ranges and presented a tendency to decrease towards finer particle sizes. The dry state showed a varia-

TABLE 3: Limit values for the recycling of construction materials according to the RBV.

Parameter		Unit	Quality classes			
			U-A	U-B	U-E	H-B
Leaching tests (L/S 10)	pH	[1]	7.5$^{1)}$ - 12.5$^{2)}$			up to 12.5$^{2)}$
	Electric conductivity	[mS/m]	150			-
	Cr_{Tot}	[mg/kg (DM)]	0.6	1	0.6	1
	Co	[mg/kg (DM)]	-		1	-
	Cu	[mg/kg (DM)]	1	2	1	2
	Mo	[mg/kg (DM)]	-		0.5	-
	Ni	[mg/kg (DM)]	0.4	0.6	0.4	-
	NH_4^+	[mg/kg (DM)]	4	8	4	8
	Cl^-	[mg/kg (DM)]	800	1,000	800	1,000
	NO_2^-	[mg/kg (DM)]	2			-
	SO_4^{2-}	[mg/kg (DM)]	2,500	6,000	2,500	6,000
	TOC	[mg/kg (DM)]	100	200	100	200
	KW index	[mg/kg (DM)]	-		5	-
	MBAS assay	[mg/kg (DM)]	-		1	-
Solid matter	As	[mg/kg (DM)]	-		50 / 200$^{4)}$	-
	Pb	[mg/kg (DM)]	150	150 / 500$^{3), 4)}$		
	Cd	[mg/kg (DM)]	-		2 / 4$^{4)}$	-
	Cr_{Tot}	[mg/kg (DM)]	90 / 300$^{4)}$	90 / 700$^{4)}$	300 / 700$^{4)}$	90 / 700$^{4)}$
	Co	[mg/kg (DM)]	-		50	-
	Cu	[mg/kg (DM)]	90 / 300$^{4)}$	90 / 500$^{4)}$	100 / 500$^{4)}$	90 / 500$^{4)}$
	Ni	[mg/kg (DM)]	60 / 100$^{5)}$	60	100	60
	Hg	[mg/kg (DM)]	0.7		1 / 2$^{4)}$	0.7
	Zn	[mg/kg (DM)]	450		500 / 1,000$^{4)}$	450
	KW index	[mg/kg (DM)]	150	200	150	200
	Σ16PAHs/EPA	[mg/kg (DM)]	12	20	12	20

Notes: DM= dry matter.

1) For natural non-contaminanted rock the pH-range starts from 6.5.

2) If the pH value and/or the electrical conductivity are exceeded, freshly broken concrete containing recycling building materials can be subjected to rapid carbonation based on the ÖNORM S 2116-3 "Investigation of Stabilized Waste, Part 3: Rapid Carbonation", issued on January 1, 2010. In this case, the eluate must be examined again. In any case, the limit values must be observed after carbonation. This applies to both the pH value and electrical conductivity.

3) If the Pb content exceeds 150 mg/kg (DM), the Pb concentration in the eluate must be determined and a limit value of 0.3 mg/kg (DM) must be complied with.

4) The higher limit value applies if background concentrations can be demonstrated.

5) No limit value applies if background concentrations can be demonstrated.

tion of the DM content between 97.3 wt.% and 97.1 wt.% among the particle size ranges, which also presented a decreasing tendency (albeit very slight) towards finer particle sizes. This can be explained by the greater presence of impurities in the owc state than in the dry state, which tend to absorb/adsorb water and whose amount has also shown an increasing trend with the decrease in particle size. Furthermore, this information reveals that the material processed in the dry state with an initial DM content of 100.0 wt.% absorbed/adsorbed between 2.7 wt.% and 2.9 wt.% of moisture from the environment along the mechanical processing, which suggests that a closed moisture-free mechanical processing would be needed to maintain the water content below those levels. The calculated DM contents of the mixed single particle size range 90-4.5 mm accounted for 80.3 wt.% in the owc state and 97.2 wt.% in the dry state.

The NCV was significantly higher in the dry state than in the owc state although it was normalized to DM. This means that either during mechanical processing in the owc state calorific materials were lost to the fine fractions <4.5 mm or inert materials were lost to the same fraction during processing in the dry state. It is suggested that the latter is the case, i.e. inorganic materials remained attached to the calorific fractions in the owc state to a greater extent than in the dry state. The NCV was higher for coarser fractions, i.e. combustibles occurred rather in coarser particle size, and varied from 15.8 MJ/kg (DM) to 7.9 MJ/kg (DM) in the owc state and from 17.6 MJ/kg (DM) to 8.9 MJ/kg (DM) in the dry state. As a mixed single particle size range, the NCV of the "Combustibles" fractions accounts for 12 MJ/kg (DM) in the owc state and 14.4 MJ/kg (DM) in the dry state. The values of the NCV referring to the original substance (as received (ar)) are in the range of those us-

TABLE 4: Permited use of recycled construction aggregates per quality class according to the RBV.

Class	Description	Unbound application1) without low permeable, bound top layer or base layer	Unbound application1) under low permeable, bound top layer or base layer	Production of concrete from the strength class C 12/15 on or strength class C 8/10 from the exposure class XC1 on	Production of asphalt
U-A	Aggregates for the unbound use, as well as for the hydraulic or bituminous bound use	Yes	Yes	Yes	Yes
U-B	Aggregates for the unbound use, as well as for the hydraulic or bituminous bound use	No	Yes 2)	Yes	Yes
U-E	Aggregates for the unbound use, as well as for the hydraulic or bituminous bound use	Yes 2), 3)	Yes 2)	Yes	Yes
H-B	Aggregates exclusively for the production of concrete from the strength class C 12/15 on or from the strength class C 8/10 from the exposure class XC1 on	No	No	Yes	No

Notes:

1) Including manufacture of concrete under strength class C 12/15 or up to strength class C 8/10 under exposure class XC1.

2) Use according to § 13 Z1 (unless a water-legal license for the use of recycled building materials is not available in protected areas, not in designated zones of sanctuaries, not in designated protected areas, not in and immediately above groundwater and not in surface water).

3) Only in the trapezoid of the track body as a base layer (§ 13 Z 4).

able in fluidized bed incinerators (Sarc & Lorber, 2013) for the particle size ranges 90-30 mm and 30-10 mm, but below that range for the particle size range 10-4.5 mm. The ranges of NCV values of the "Combustibles" fractions are in the same range as those obtained for individual calorific fractions in a previous LFM project in Austria (Wolfsberger et al., 2015).

The AC is significantly higher for the samples processed in the owc state than for those processed in the dry state. This is associated with the presence of a larger amount of surface defilements in the owc state and the predominant inorganic nature of surface defilements. Contrary to the NCV, the AC of the "Combustibles" fractions increased with the decrease in particle size, which can also be explained by the increase in the amount of impurities as particle size decreased and the directly proportional correlation between the amount of impurities composed predominantly of inorganic compounds and the AC. In the dry state the AC reached values above 50 wt.% (DM) in the particle size range 10-4.5 mm, while it did as well in the particle size ranges 30-10 mm and 10-4.5 mm in the owc state. Amounts of 47.4 wt.% (DM) and 38.2 wt.% (DM) of AC were calculated for the mixed single particle size range 90-4.5 mm in the owc and dry states, respectively. The AC values of the "Combustibles" fractions were in the range of low quality supplier materials for RDF production from municipal solid waste and industrial or commercial waste (Sarc & Lorber, 2013), which show that the quality of the combustible materials obtained through LFM for the production of RDF might not be very far from that of more recent types of waste.

The Cl and S concentrations in the "Combustibles" fractions decreased with decreasing particle size in both the owc and dry states. As a mixed single particle size range, the concentrations of Cl and S are in the range of 0.9-1.2 wt.% and 0.5-0.6 wt.%, respectively, for both states; which is in agreement with commercial RDF (Sarc & Lorber, 2013). The determined concentrations were higher for the material processed in the dry state, which suggests that Cl and S are enriched in combustible materials (e.g. as PVC for Cl and vulcanized plastics for S) and not in inorganic surface defilements. The F and B concentrations were insignificant. The C contents decreased with decreasing particle size in both the owc and dry states, and were higher for the fractions treated in the dry state, which suggests dominance of organic carbon. This can be confirmed by the TOC values, which indicated that practically the entire C content is organic. Amounts of 33.0 wt.% (DM) and 39.7 wt.% (DM) account for the C content of the mixed single particle size range in the owc and dry states, respectively. The H content showed the same tendency as Cl, S and C contents, both with respect to particle size and processing state, which suggests its presence in combustible materials. H presented concentrations in the range of 2.9-5.8wt.% (DM) in the owc state and 3.2-6.8 wt.% (DM) in the dry state. For N, which showed respective concentrations in the range of 1.0-2.0 wt.% (DM) and 0.9-1.4-wt.% (DM) in the owc and dry states, a decrease with decreasing particle size was observed; but not clear correlation with the processing state (i.e. owc and dry states) was identified. The concentrations of Σ16PAHs/EPA were in the range of 10.9-13.3 mg/kg (DM) in the owc state and 9.4-13.4 mg/kg (DM) in the dry state, and did not seem to be influenced by the processing state and are highest for the intermediate particle size range (i.e. 30-10 mm) in both states. As for the Hg concentrations, no significant variations between the owc and dry states for the particle size ranges 90-30 mm and 10-4.5 mm were shown. The particle size range 30-10 mm presented the highest concentrations of Hg in the owc state, while 10-4.5 mm did so in the dry state. The concentrations of Hg ranged from 0.06-0.30 mg/MJ (ar) in the owc state and from 0.07-0.20 mg/MJ (ar) in the dry state. The Hg concentrations are rather enriched in the finer particle size ranges, which suggests its association with surface defilements.

The pseudo-total contents of the heavy metals As, Cd, Co, Cr, Hg, Ni, Pb and Sb in the "Combustibles" fractions per particle size range and state, and as a single particle size range mixed in the original proportions of each particle

TABLE 5: Laboratory results of the solid matter analyses of the "Combustibles" fractions.

Parameter	Unit	90-30 mm				30-10 mm				10-4.5 mm				90-4.5 mm (mixed in original proportions)			
		Owc		Dry		Owc		Dry		Owc		Dry		Owc		Dry	
		Mean	Std. error	Mean	Std. error	Mean	Std. error	Mean	Std. error	Mean	Std. error	Mean	Std. error	Mean	Std. error	Mean	Std. error
DM	[wt.% (ar)]	86.70	1.69	97.27	0.83	77.17	1.90	97.20	0.11	74.53	0.43	97.13	0.07	80.24	0.81	97.22	0.41
NCV [1]	[MJ/kg (DM)]	15.80	0.41	17.60	1.63	10.53	0.95	13.40	1.13	7.87	1.24	8.93	0.24	11.97	0.48	14.39	0.90
	[MJ/kg (ar)]	13.40	0.71	17.07	1.49	7.60	0.98	12.93	1.08	5.23	0.91	8.57	0.26	9.31	0.43	13.92	0.82
AC	[wt.% (DM)]	33.00	4.21	26.10	0.97	52.87	1.12	42.70	1.93	62.70	4.28	57.70	1.41	47.38	1.37	38.20	1.26
Cl	[wt.% (DM)]	1.48	1.16	1.91	0.69	0.63	0.16	0.73	0.28	0.16	0.01	0.16	0.01	0.86	0.47	1.16	0.37
F	[wt.% (DM)]	0.02	0.00	0.02	0.00	0.02	0.00	0.02	0.00	0.02	0.00	0.02	0.00	0.02	0.00	0.02	0.00
S	[wt.% (DM)]	0.58	0.29	0.74	0.12	0.46	0.07	0.40	0.02	0.41	0.04	0.38	0.03	0.50	0.12	0.55	0.04
Br	[wt.% (DM)]	0.02	0.00	0.02	0.01	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	-	-	-	-
C	[wt.% (DM)]	42.53	6.67	49.17	2.65	29.83	1.54	35.93	1.88	21.83	0.66	24.67	0.73	32.98	2.41	39.67	1.39
H	[wt.% (DM)]	5.82	1.05	6.80	0.75	3.84	0.18	4.53	0.22	2.90	0.08	3.18	0.05	4.40	0.35	5.30	0.39
N	[wt.% (DM)]	1.99	2.00	1.40	0.49	1.04	0.08	1.23	0.23	0.97	0.03	0.94	0.04	1.39	0.78	1.24	0.15
TOC	[wt.% C (DM)]	43.37	5.35	52.13	2.58	28.40	2.01	37.57	2.69	18.97	1.52	20.60	2.16	32.11	1.54	40.68	2.45
Σ16PA Hs/EPA	[mg/kg (DM)]	10.89	12.77	9.38	4.79	21.33	19.45	18.23	5.87	13.27	2.68	13.40	3.42	15.67	5.21	13.01	4.15
Parameter	**Unit**	**Median**	**80th percentile**	**Median**	**80th percentile**	**Median**	**80th percentile**	**Median**	**80th percentile**	**Median**	**80th percentile**	**Median**	**80th percentile**	**Median**	**80th percentile**	**Median**	**80th percentile**
Hg	[mg/MJ (ar)]	0.06	0.07	0.07	0.09	0.30	0.31	0.11	0.11	0.20	0.23	0.20	0.24	0.15	0.16	0.09	0.11
Ba	[mg/MJ (DM)]	61.39	239.49	21.02	22.05	112.97	218.92	66.42	83.88	136.02	147.46	102.99	103.66	89.94	217.66	42.38	49.18
Be	[mg/MJ (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
Cu	[mg/MJ (DM)]	7.59	20.13	14.20	51.36	18.99	24.68	11.19	40.75	25.42	30.76	27.99	30.00	17.41	20.92	29.89	42.45
Mo	[mg/MJ (DM)]	0.89	0.92	0.57	0.64	0.52	0.62	0.37	0.38	0.92	1.09	0.88	1.09	0.81	0.82	0.55	0.57
Mn	[mg/MJ (DM)]	13.92	16.20	7.95	8.98	26.58	27.72	19.40	19.40	40.68	42.20	33.58	33.58	21.50	23.67	14.11	15.09
Se	[mg/MJ (DM)]	<d.l.	-	<d.l.	-	0.25	0.27	<d.l.	-	0.42	0.43	0.03	0.39	-	-	-	-
Tl	[mg/MJ (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
V	[mg/MJ (DM)]	0.82	1.09	0.63	0.76	2.28	2.79	1.12	1.39	3.56	3.64	2.69	2.75	1.66	2.03	1.18	1.18
Zn	[mg/MJ (DM)]	77.22	92.41	56.82	62.27	131.96	132.53	163.43	178.66	179.24	186.10	150	153.36	112.43	112.54	102.09	103.89

Notes: <d.l. = amount below detection limit. ar= as received. DM= dry mass. n=3, std. error with Ci of 95%.[1] The gross calorific value (GCV) was determined experimentally according to the DIN 51900-1. A fixed correction factor of f= 0.92, based on the GCV, was used for the calculation of the NCV according to the "AQS Richtlinie (2001)".

size range are shown in the form of box-and-whisker plots in Figure 5.

The data in Figure 5 show that the concentrations of As, Cd, Co, Ni and Pb increase with decreasing particle size, which suggests that they are present in the inorganic defilements or adsorbed to their surfaces. For Cr, Hg, and Sb this trend is less pronounced. For As, Cd, Co, and mostly Pb and Ni, concentrations in the owc state processed samples are higher than in those processed in the dry state, which confirms their association with inorganic defilements. Cr concentrations in the coarsest particle size range are higher for the material processed in the dry state, whereas in the finer particle size ranges they are higher for those materials processed in the owc state. This suggests that one part of Cr is present in larger partices, e.g. textiles due to tanning agents, whereas another part is present in fine-grained surface defilements.

After comparing the results with the limit values set in the AVV (Table 2), it was observed that the concentrations of the particle size range 90-30 mm in the owc state extensively complied with the limit values of all heavy metals for use in power plants; except Pb, which was only exceeded for the 80th percentile by a minuscule amount. In turn, the same particle size in the dry state presented low concentrations of all heavy metals as well, failing only to comply with the median and 80th percentile limit values for Cd for use in power plants by small amounts. However, the median concentrations of Hg in the owc and dry states were

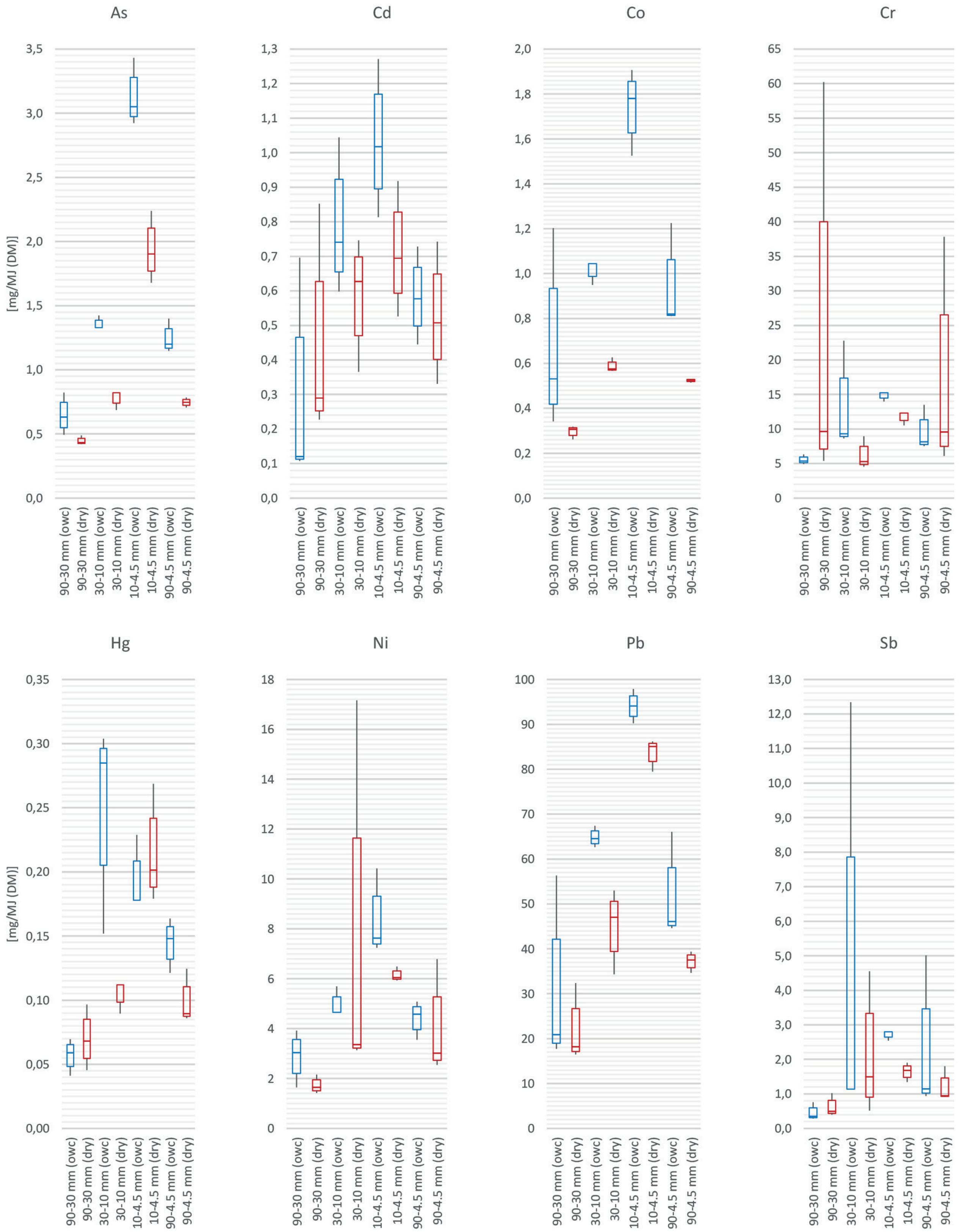

FIGURE 5: Heavy metals concentrations of the "Combustibles" fractions in the owc (blue) and dry (red) states.

close to that of the limit value and, hence, this element could also be problematic. The particle size range 30-10 mm failed to comply with the limit values of Cd and Pb for both median and 80th percentile in the owc and dry states. Additionally, that particle size range exceeded the median and 80th percentile limit values of Hg in the owc state, while in the dry state only the limit value for the median was exceeded. The concentrations of Cd, Hg and Pb of the particle size range 10-4.5 mm were above the limit values for the median and 80th percentiles in both owc and dry states. In the owc state, the concentration of As exceeded the median and 80th percentile limit values, while the median concentration of Co was above the limit value as well.

According to the previous data, it can be said that the quality of the "Combustibles" fractions tends to decrease with particle size. That can be explained by the presence of heavy-metal bearing fine-grained particles. If the particle size ranges 90-30 mm, 30-10 mm and 10-4.5 mm were to be mixed in the original proportions, the resulting single particle size range 90-4.5 mm of the "Combustibles" fractions would exceed the median and 80th percentile limit values for Hg and Pb in the owc state, while the median for Cd would also be above the limit value. In the dry state, the particle size range 90-4.5 mm would exceed the median and 80th percentile limit values of Cd, as well as the median limit values of Hg and Pb.

3.1.1 Valorization of Combustibles fractions as RDF

Previous investigations have shown that plastics from (E)LFM are most likely not suitable for recycling routes and, thus, their valorization should be directed to energy recovery through thermochemical processes, such as incineration, pyrolysis and gasification, or to the production of monomers and industrial chemical precursors (Canopoli, Fidalgo, Coulon, & Wagland, 2018). This might be the case, since LFM plastic waste is commonly characterized by its high ash, impurities and heavy metals contents (Canopoli et al., 2018).

In general, the "Combustibles" fractions recovered in the present case study could be valorized as SRF in (co-) incineration, power and cement plants in the EU, under certain circumstances depending on the type of plant and given that the corresponding plant complies with the applicable emission limit values established in the Directive on the Incineration of Waste (2000/76/EC), since the recovered "Combustibles" fractions meet the specifications set in the EN 15359:2011, in both the owc and dry states. Furthermore, the "Combustibles" fractions could be valorized mixed in one single particle size range (i.e. 90-4.5 mm) in their original proportions (i.e. 38 wt.% of 90-30 mm, 41 wt.% of 30-10 mm and 21 wt.% of 10-4.5 mm in the owc state; 47 wt.% of 90-30 mm, 31 wt.% of 30-10 mm and 22 wt.% of 10-4.5 mm in the dry state) or individually, separated in the particle size ranges of the mechanical processing (i.e. 90-30 mm, 30-10 mm and 10-4.5 mm). The latter approach is reasonable for those cases in which the coarser fraction can be incinerated at a lower price, or even for revenue, in co-incineration plants and only the finer fractions need to be incinerated at higher prices in incineration plants. Altogether, the "Combustibles" fractions corresponded to a SRF of class-code NVC 5; Cl 3; Hg 3 in the owc state and of NVC 4; Cl 4; Hg 3 in the dry state. Individually, the particle size range 90-30 mm corresponds to a SRF of class-code NVC 3; Cl 4; Hg 3, 30-10 mm to a class-code of NVC 5; Cl 2; Hg 5 and 10-4.5 mm to one of NVC 5; Cl 1; Hg 4 in the owc state. In the dry state, the particle size ranges 90-30 mm, 30-10 mm and 10-4.5 mm correspond to SRF of class-codes: NVC 3; Cl 5; Hg 3, NVC 4; Cl 3; Hg 3 and NVC 5; Cl 1; Hg 4, respectively. Nevertheless, it is important to stress that legislation on waste may vary from country to country in the EU and additional restrictions, as well as stricter limit values can be applied. It is also relevant to note that the recovered combustible fractions from the fine fractions are likely to be valorized together with those recovered from the coarse fractions (i.e. the 2D >200 mm and 2D 200-90 mm fractions in the MSG case study), which might have a significant positive impact on the quality of the whole recovered combustible fraction, since the combustible fractions recovered from the coarse fractions of (E)LFM frequently present higher NCVs and lower amounts of organic and inorganic pollutants, and account for a considerable share of the processed material.

Some of the circumstances previously mentioned are that not all classes of SRF are suitable for all types of plants (refer to CEN / TR 15508). For example, if cement and lime kilns and power plants use 100% SRF as fuel and have an emission limit of Hg of 0.05 mg/m^3, only SRF class Hg 1 is suitable for those plants. SRF with a class Hg 5 could only be used in those plants if this class of SRF represents less than 100% of the fuel mixture. For other SRF classes, the specific transfer factor for a given process and the proportion of SRF determine which classes can be used without improving the transfer conditions. Examples of transfer factors for existing processes are given in the CEN / TR 15508. Additionally, SRF should not be used as fuel if less heat energy is generated and available for the plant-related process, than is consumed during the combustion of the SRF and, therefore, is not available for the process. As a result, for example, the use of SRF class NCV 5 in systems that require a higher minimum heating value for energy production should be avoided.

However, in Austria, where regulations are stricter than in many other EU countries, the "Combustibles" fractions would need to be subjected to a cleaning process, in which the amount of surface defilements and impurities could be further reduced, in order to be valorized as RDF in co-incineration plants.

An alternative to both further cleaning for subsequent co-incineration and direct incineration is the use of pyrolysis and gasification as thermo-chemical valorization methods for the combustible fractions of landfill-mined material in order to produce syngas. Subsequently to the pyrolysis/gasification process, the molten ash residue is vitrified; producing a glassy slag. This is the principal approach in the NEW-MINE project, which proposes the utilization of plasma gasification as alternative thermo-valorization method for the high calorific fractions from landfill-mined waste. The plasma gasification investigated in the NEW-MINE project can cope with RDF materials with higher inorganic pollutant contents, since those pollutants can be immobilized in the vitrified residue. The gasification process of SRF from municipal solid waste and industrial waste was studied in Zaini, Yang, & Jönsson, 2017; whereas the pyrolysis/gasification of RDF from landfill-mined waste was successfully tested in Zaini, García López, Pretz, Yang, & Jönsson, 2019 on a laboratory scale. It has also been demonstrated that thermal treatment of the glassy slag yielded glass-ceramics with very low leaching of Cr, Cu, Co, Cd and Ni (Rabelo Monich et al., 2020), as well as that inorganic polymer binders can be produced from the (semi-)vitreous material obtained as by-product in plasma gasification of waste materials (Ascensão et al., 2019; Machiels et al., 2017). Both glass-ceramics and inorganic polymers are higher value-added products that could be used to replace raw materials in construction applications, such as tiles, bricks and glass foams (Monich et al., 2018; Rabelo Monich, Dogrul, Lucas, Friedrich, & Bernardo, 2019; Rincón, Marangoni, Cetin, & Bernardo, 2016), as well as in the production of concrete (Ascensão et al., 2019; Machiels et al., 2017). Therefore, in contrast to conventional (co-)incineration, plasma gasification might offer a potential WtE valorization route for the combustible fractions obtained from the fine fractions of landfill-mined waste, which in the present case study accounted for 12.5 wt.% and 9.0 wt.% of the total amount of the fine fractions <90 mm in the owc and dry states, respectively.

3.2 Inert fractions

The chemical composition of the “Inert” fractions per particle size range (i.e. 90-30 mm, 30-10 mm, 10-4.5 mm and 90-4.5 mm (mixed in original proportions)) and state (i.e. the owc and dry states) was determined through XRF analyses. This information is displayed graphically in the form of stacked columns in Figure 6.

The information in Figure 6 unveils that most of the “Inert” fractions was composed of silicon dioxide (SiO_2), followed by aluminium oxide (Al_2O_3), calcium oxide (CaO), iron oxide (Fe_2O_3) and sodium oxide (Na_2O). Chemically, there are no significant differences between the samples processed in the owc state and those processed in the dry state. The LOI was higher for the finest particle size ranges, as moisture is mainly adsorbed by finer particles. Al_2O_3 and CaO concentrations do not significantly change among particle size ranges, whereas Fe_2O_3 increased with the decrease in particle size. This can be explained by the formation of iron hydroxides in the landfill due to the oxidation of Fe^{2+} to Fe^{3+} in the leachate and also by the corrosion of iron particles. A similar behavior is observed for Mn, which is explained analogously by the precipitation of Mn hydroxides due to the oxidation of Mn^{2+}/Mn^{3+} to Mn^{4+}. As Cr showed a similar tendency, it is suspected that Cr formed secondary Cr(III) phases as described in Sedlazeck, Höllen, Müller, Mischitz, & Gieré, 2017. Contrary as for Fe and Mn, the higher valent form of Cr was more soluble than the lower valent form.

Additionally, solid matter laboratory analyses were peformed to the “Inert” fractions for parameters such as S, C, KW index, N and certain heavy metals (i.e. Cr, Co, Ni, Cu, Zn, As, Cd, Hg and Pb), as well as DM, Σ16PAHs/EPA and TOC

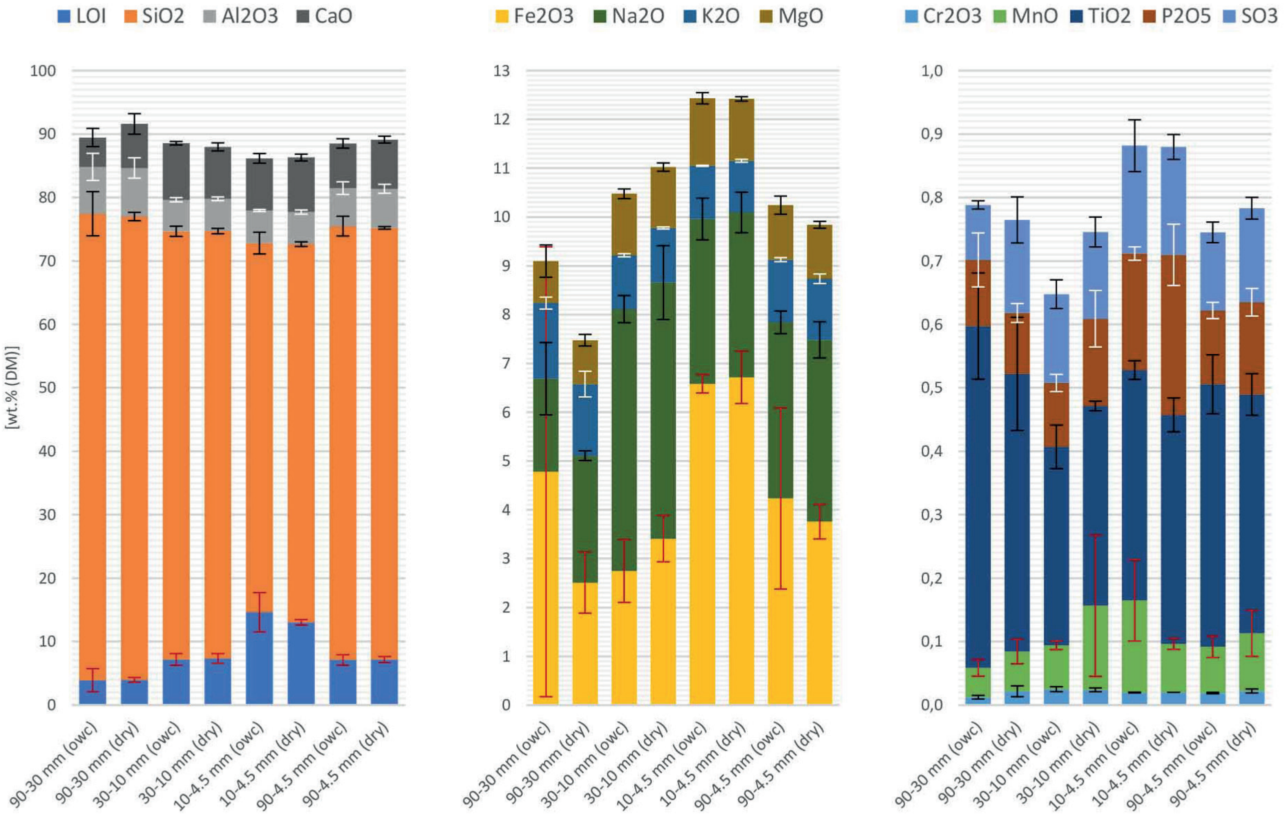

FIGURE 6: Chemical composition of the “Inert” fractions from XRF analyses in the owc and dry states.

contents, per particle size range and state. Table 6 presents a summary of the results of those laboratory analyses.

The results in Table 6 show that the particle size range 90-30 mm presented the best quality among all particle size ranges in both the owc and dry states, complying with all solid matter parameters for all quality classes (i.e. U-A, U-B, U-E and H-B from Table 3); except for the concentration of Pb in the dry state, which was slightly exceeded for all quality classes. However, the standard error of this parameter significantly exceeds the mean value itself and shows the strongest variation among all parameters for that state; suggesting the presence of outliers. Moreover, the amount of Pb was significantly exceeded in the particle size range 10-4.5 mm in both states, whereas the particle size range 30-10 mm complied with the limit value for all quality classes in both states as well. The concentration of Pb in the leaching tests of the "Inert" fractions as a mixed single particle size range 90-4.5 mm can be expected below 0.3 mg/kg (DM) in both states, since the highest concentration determined from all samples of all particle size ranges was 0.26 mg/kg (DM) (Table 7), which was one order of magnitude above those of all other samples. Provided that background concentrations of Pb in the site of application can be proven, a limit value of 500 mg/kg DM would apply to these fractions and, hence, all particle size ranges, except 10-4.5 mm in the dry state, would meet the limit value for all quality classes.

In terms of quality, the particle size range 30-10 mm followed 90-30 mm. In the dry state, the particle size range 30-10 mm complied with all parameters for all quality classes; except for the hydrocarbons content (KW index), which slightly exceeded the limit values for the quality classes U-A and U-E. In the owc state, this particle size range exceeded the limit values for hydrocarbons content for all quality classes, in which classes U-B and H-B were only slightly exceeded. The concentration of Cd in this particle size range exceeded the lower limit value for quality class U-E and presented the same value as the higher limit value (applicable if background concentrations can be demonstrated) in the owc state. However, the standard error of the Cd content in that state suggests outliers and , in addition, Cd content is not relevant for classes U-A, U-B and H-B. The Zn concentration was also exceeded by this particle size range in the owc state for classes U-A, U-B and H-B, as well as the lower limit value for class U-E; meaning that if background concentrations of Zn can be proven, the higher limit value for class U-E would not be exceeded.

The particle size range 10-4.5 mm showed the lowest quality, since the limit values for hydrocarbons, Zn, Cd and Pb were exceeded for all quality classes in both the owc and dry states. No significant differences were identified between the quality of both states in this particle size range; except for Pb, which presented a higher concentration in the dry state.

As a mixed single particle size range 90-4.5 mm, the "Inert" fractions would slightly exceed the limit values for hydrocarbons for the quality classes U-B and H-B in both owc and dry states, while the cocentration of Pb would exceed the limit value for class U-A and the lower limit value for classes U-B, U-E and H-B only in the dry state. In the owc state, the Zn content would exceed quality classes U-A, U-B and H-B, and the lower limit value of class U-E.

In general, it can be said that the dry state presented higher concentrations of Pb; nevertheless, a conclusive tendency cannot be confirmed due to the presence of outliers. In turn, the owc state showed consistently higher contents of hydrocarbons and Zn, which can be explained by the presence of impurities. For Cd no trend could be identified between both states.

The previous information reveals that the quality of the "Inert" fractions, in terms of the solid matter parameters analyzed, decreased with the decrease in particle size. This suggests that the quality decrease is associated with the presence of organic and inorganic impurities and, therefore, a cleaning step would be needed to reduce the concentrations of the problematic elements and compounds (especially those of hydrocarbons), and enable the utilization of the "Inert" fractions as substitute for construction aggregates in Austria. The elevated concentrations of Cd and Pb could be due to the presence of glass, since such elements have been commonly used in glass production as coloring and decorative agents in the past. Hence, the separation of glass from the "Inert" fractions, through a density separation or sensor-based sorting method, might reduce the concentrations of Cd and Pb.

In addition to the solid matter laboratory analyses, leaching tests were performed to samples of the "Inert" fractions according to the RBV. The results of the leaching tests are summarized in Table 7. After comparing the leaching tests parameters of the "Inert fractions" in Table 7 with the corresponding limit values set in the RBV, it was observed that the contents of NH_4^+ significantly exceeded the limit values in almost every case; only the particle size range 30-10 mm in the owc state complied with the limit value of classes U-B and H-B, and exceeded the limit value of classes U-A and U-E by a minuscule amount. High concentrations of NH_4^+ in landfills are in agreement with previous observations (Vollprecht, Frühauf, Stocker, & Ellersdorfer, 2019). Only with one exception, for the particle size range 90-30 mm, the amounts of NH_4^+ were lower in the owc state than in the dry state.

The amounts of anionic surfactants determined by the MBAS assay, which are the active washing components of products such as soap or detergent, were very slightly above the limit values in the particle size ranges 30-10 mm in the owc state and 10-4.5 mm in both states, whereas the amounts in the particle size ranges 30-10 mm in the dry state and 90-30 mm in both states were below the detection limit. It should be noted that the limit value in the RBV for this parameter corresponds to the detection limit of the assay and, therefore, the measured amounts could correspond to outliers.

The pH value of the particle size range 10-4.5 mm in the owc state was very slightly below the limit value of quality classes U-A, U-B and U-E; however, this fraction is suitable for quality class H-B. Hence, pH is not regarded as a problematic parameter in this fraction.

The TOC content of the particle size range 10-4.5 mm in the dry state complied with the limit values for quality classes U-B and H-B, but slightly exceeded those of class-

TABLE 6: Laboratory results of the solid matter analyses of the "Inert" fractions.

Param-eter	Unit	90-30 mm				30-10 mm				10-4.5 mm				90-4.5 mm (mixed in original proportions)			
		Owc		Dry		Owc		Dry		Owc		Dry		Owc		Dry	
		Mean	Std. error	Mean	Std. error	Mean	Std. error	Mean	Std. error	Mean	Std. error	Mean	Std. error	Mean	Std. error	Mean	Std. error
DM	[wt.%]	97.13	0.66	99.67	0.13	97.13	0.69	99.73	0.07	90.73	0.07	99.30	0.00	96.05	0.54	99.61	0.05
S	[mg/kg (DM)]	740.00	239.52	1,043.33	252.36	1,176.67	73.63	853.33	34.57	1,966.67	42.84	1,563.33	96.24	1,131.93	95.19	1,089.33	129.87
C	[wt.% (DM)]	1.42	0.45	1.47	0.06	3.33	0.74	3.66	0.48	6.24	0.39	6.32*	0.04	3.04	0.26	2.86	1.09
KW index	[mg/kg (DM)]	60.67	25.44	38.00	31.38	226.67	51.03	164.33	144.28	646.67	183.98	630.00	244.80	230.01	21.98	213.72	13.48
N	[wt.% (DM)]	0.15	0.01	0.14	0.01	0.20	0.01	0.21	0.02	0.35	0.04	0.33	0.05	0.20	0.00	0.21	0.01
Σ16PAHs/ EPA	[mg/kg (DM)]	0.25	0.43	1.70	2.27	0.68*	0.34	0.34*	0.44	3.35	0.76	8.59	6.23	0.86	0.38	2.68	1.66
TOC	[wt.% C (DM)]	0.27	0.08	0.26	0.04	1.60	0.49	2.25	0.61	4.56	0.36	4.85	0.19	1.56	0.18	1.99	0.19
Li	[mg/kg (DM)]	3.47	1.31	4.23	0.77	4.07	0.17	3.83	0.58	8.90	2.19	7.33	1.25	4.64	0.23	4.77	0.60
Be	[mg/kg (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
Na	[mg/kg (DM)]	1,356.67	329.98	1,256.67	297.32	2,250.00	1,017.75	1,836.67	136.42	1,650.00	152.24	1,640.00	167.46	1,781.73	493.43	1,549.80	136.99
Mg	[mg/kg (DM)]	1,826.67	1,857.16	1,570.00	311.14	2,130.00	425.37	2,033.33	471.26	4,583.33	768.02	3,876.67	226.70	2,422.70	799.41	2,244.27	318.98
Al	[mg/kg (DM)]	5,643.33	843.36	6,620.00	1,082.80	6,270.00	373.43	6,276.67	892.49	9,440.00	1,211.45	9,136.67	1,324.14	6,551.97	299.83	7,050.07	448.93
Si	[mg/kg (DM)]	740.00	256.30	1,376.67	257.38	713.33	66.31	643.33	56.96	530.00	166.70	556.67	42.84	693.10	153.67	932.27	104.40
P	[mg/kg (DM)]	223.33	154.47	190.00	70.67	360.00	122.40	430.00	215.90	820.00	22.63	1,056.67	252.36	382.17	41.43	467.07	91.96
K	[mg/kg (DM)]	1,523.33	164.12	1,376.67	254.63	1,383.33	94.90	1,430.00	92.63	2,043.33	213.61	1,963.33	202.53	1,552.93	72.21	1,524.93	36.85
Ca	[mg/kg (DM)]	20,333.33	17,078.01	22,290.00	21,136.07	30,400.00	1,584.25	22,900.00	4,834.23	35,900.00	2,856.05	36,000.00	1,821.15	27,207.67	6,861.29	25,525.80	9,317.40
Ti	[mg/kg (DM)]	450.00	186.29	373.33	101.42	253.33	13.07	206.67	6.53	276.67	17.29	290.00	22.63	337.93	81.42	295.00	37.09
V	[mg/kg (DM)]	5.23	1.83	18.27	23.26	10.77	6.12	8.70	4.71	15.67	3.46	17.00	3.92	9.33	3.71	14.54	9.27
Cr	[mg/kg (DM)]	15.33	4.57	29.00	29.42	22.00	3.92	19.33	3.27	46.33	24.41	37.67	3.46	23.40	7.43	27.43	13.66
Mn	[mg/kg (DM)]	125.00	65.25	253.33	147.25	203.33	55.82	636.67	856.54	883.33	651.47	360.00	29.94	286.82	150.91	414.80	256.38
Fe	[mg/kg (DM)]	27,000.00	34,326.87	10,433.33	2,883.56	19,100.00	4,901.31	19,700.00	3,063.71	42,600.00	1,555.70	44,600.00	4,708.08	26,334.00	12,768.72	21,286.00	2,268.87
Co	[mg/kg (DM)]	4.40	1.02	2.60	0.79	3.30	0.34	2.57	0.17	7.57	1.75	5.57	0.57	4.48	0.23	3.24	0.35
Ni	[mg/kg (DM)]	8.73	1.21	7.43	0.17	14.00	1.13	11.33	1.73	31.33	6.23	26.33	3.97	14.79	1.99	13.00	0.79
Cu	[mg/kg (DM)]	10.50	5.39	9.60	2.40	31.33	14.42	52.67	26.74	74.33	19.93	84.00	35.30	30.10	7.35	41.47	14.59
Zn	[mg/kg (DM)]	83.00*	52.92	73.33	26.23	863.33	1,017.84	266.67	201.26	1,193.33	639.57	1,065.00*	499.80	588.15	323.91	283.00	186.87
As	[mg/kg (DM)]	30.67	40.51	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	-	-	<d.l.	-
Se	[mg/kg (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
Sr	[mg/kg (DM)]	74.00	55.07	96.33	29.08	95.33	6.43	73.00	6.88	116.67	13.07	103.33	6.53	90.21	23.39	89.47	11.13
Mo	[mg/kg (DM)]	<d.l.	-	<d.l.	-	1.53	0.33	<d.l.	-	1.97	0.47	3.47	0.52	-	-	-	-
Pd	[mg/kg (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
Ag	[mg/kg (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	2.77	3.46	1.07	0.13	-	-	-	-
Cd	[mg/kg (DM)]	<d.l.	-	<d.l.	-	4.00	5.88	<d.l.	-	4.17	0.86	4.43	4.68	-	-	-	-
Sn	[mg/kg (DM)]	3.87	1.44	4.43	4.11	25.33	2.61	27.33	14.24	130.00	49.33	170.00	49.33	34.33	7.45	49.10	12.15
Sb	[mg/kg (DM)]	1.53	1.05	<d.l.	-	1.57	0.46	2.43	2.62	2.53	0.17	3.10	0.41	1.72	0.29	-	-
Te	[mg/kg (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
Ba	[mg/kg (DM)]	77.33	42.36	106.67	6.53	105.00	14.97	104.33	26.21	840.00	594.82	360.00	79.21	218.61	116.05	161.56	20.08
W	[mg/kg (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
Hg	[mg/kg (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
Tl	[mg/kg (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
Pb	[mg/kg (DM)]	34.00*	1.96	186.00	251.71	136.67	52.27	58.50*	26.46	250.00*	0.00	836.67	191.48	95.03	36.26	276.23	121.92

Notes: <d.l.= amount below detection limit. ar= as received. DM= dry mass. n=3, std. error with Ci of 95%.
**This parameter was determined from 2 measurements (n=2) instead of 3 (n=3).*

es U-A and U-E.

Mixed as a single particle size range 90-4.5 mm, the "Inert" fractions are expected to comply with all parameters of the leaching tests: except for NH_4^+ and anionic surfactants. The contents of NH_4^+ were generally larger in the owc state than in the dry state, which suggests that NH_4^+ is adsorbed to fine-grained particles which in turn are adhered to particles in the owc state and removed in the dry state. No

TABLE 7: Laboratory results of the leaching tests of the "Inert" fractions.

Parameter	Unit	90-30 mm				30-10 mm				10-4.5 mm			
		Owc		Dry		Owc		Dry		Owc		Dry	
		Mean	Std. error	Mean	Std. error	Mean	Std. error	Mean	Std. error	Mean	Std. error	Mean	Std. error
pH	[1]	9.13	0.17	10.30	0.69	8.23	0.69	8.87	0.46	7.27	0.26	7.70	0.00
Electric conductivity	[mS/m]	34.07	4.35	30.17	16.41	40.03	19.65	55.80	38.44	80.00	4.30	60.00	5.63
NH_4^+	[mg/kg (DM)]	30.67	14.06	20.00	8.98	4.40	1.58	29.33	1.31	16.00	2.99	64.33	9.62
Cl^-	[mg/kg (DM)]	113.67	22.92	87.33	23.58	94.67	40.25	43.33	4.71	210.00	11.32	140.00	11.32
SO_4^{2-}	[mg/kg (DM)]	980.00	197.30	663.33	102.68	1,090.00	680.09	1,180.00	1,280.07	2,416.67	62.32	1,840.00	238.44
MBAS assay	[mg/kg (DM)]	<d.l.	-	<d.l.	-	1.23	0.36	<d.l.	-	1.07	0.13	1.07	0.13
TOC	[mg/kg (DM)]	52.00	9.09	49.90	20.68	50.23	12.77	58.77	17.60	96.17	2.52	125.67	8.03
KW index	[mg/kg (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	0.51	0.02	<d.l.	-
NO_2^-	[mg/kg (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
F^-	[mg/kg (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
Li	[mg/kg (DM)]	0.05	0.02	0.05	0.02	0.05	0.02	0.03	0.01	0.08	0.01	0.04	0.01
Be	[mg/kg (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
Na	[mg/kg (DM)]	89.67	14.77	64.00	13.34	95.67	28.09	63.33	10.51	183.33	6.53	133.33	6.53
Mg	[mg/kg (DM)]	28.67	12.41	10.57	7.73	42.67	23.26	23.67	15.20	103.00	6.88	66.00	8.84
Al	[mg/kg (DM)]	2.60	2.16	3.77	1.30	3.77	1.14	8.37	7.47	1.63	0.24	1.43	0.07
Si	[mg/kg (DM)]	59.00	18.70	135.00	103.09	25.33	3.64	27.33	11.78	19.00	1.13	23.67	1.73
P	[mg/kg (DM)]	0.64	0.47	0.23	0.10	0.22	0.07	0.56	0.30	0.30	0.04	0.74	0.12
K	[mg/kg (DM)]	100.67	9.22	86.33	10.45	109.33	40.51	113.33	26.13	213.33	6.53	220.00	11.32
Ca	[mg/kg (DM)]	546.67	180.47	466.67	243.32	1,013.33	567.65	713.33	523.16	1,486.67	199.35	996.67	444.99
Ti	[mg/kg (DM)]	0.02	0.01	0.04	0.02	0.01	0.00	0.02	0.01	0.02	0.00	0.02	0.01
V	[mg/kg (DM)]	0.07	0.03	0.76	1.11	0.01	0.00	0.07	0.06	<d.l.	-	<d.l.	-
Cr	[mg/kg (DM)]	<d.l.	-	0.02	0.00	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
Mn	[mg/kg (DM)]	0.05	0.03	0.04	0.03	0.09	0.08	0.06	0.05	0.31	0.05	0.57	0.17
Fe	[mg/kg (DM)]	0.64	0.21	0.65	0.54	0.59	0.12	0.88	0.44	1.51	0.57	1.24	0.55
Co	[mg/kg (DM)]	0.02	0.01	0.01	0.00	<d.l.	-	<d.l.	-	0.01	0.00	0.02	0.00
Ni	[mg/kg (DM)]	0.05	0.01	0.03	0.01	0.05	0.02	0.08	0.03	0.10	0.01	0.16	0.02
Cu	[mg/kg (DM)]	0.11	0.01	0.12	0.10	0.10	0.07	0.34	0.28	0.15	0.03	0.24	0.00
Zn	[mg/kg (DM)]	0.06	0.01	0.04	0.02	0.06	0.06	0.06	0.00	0.31	0.12	0.22	0.07
As	[mg/kg (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
Se	[mg/kg (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
Sr	[mg/kg (DM)]	1.07	0.13	0.93	0.37	1.51	0.89	1.09	0.89	2.63	0.17	2.07	0.17
Mo	[mg/kg (DM)]	0.13	0.09	0.09	0.05	0.05	0.02	0.06	0.01	0.06	0.01	0.15	0.02
Pd	[mg/kg (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
Ag	[mg/kg (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
Cd	[mg/kg (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
Sn	[mg/kg (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	0.02	0.00
Sb	[mg/kg (DM)]	0.01	0.00	0.01	0.00	0.03	0.03	0.03	0.03	0.03	0.01	0.05	0.02
Te	[mg/kg (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
Ba	[mg/kg (DM)]	0.31	0.03	0.27	0.11	0.48	0.25	0.44	0.22	0.91	0.05	0.88	0.02
W	[mg/kg (DM)]	0.02	0.01	0.03	0.03	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
Hg	[mg/kg (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
Tl	[mg/kg (DM)]	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-	<d.l.	-
Pb	[mg/kg (DM)]	0.02	0.00	0.02	0.01	0.02	0.01	0.26	0.43	0.05	0.02	0.03	0.01

Notes: <d.l.= amount below detection limit. ar= as received. DM= dry mass. n=3, std. error with Ci of 95%.

clear trend was identified regarding the anionic surfactants among the particle size ranges and states.

The previous information suggests that, in general, the quality of the "Inert" fractions could be improved if handled as a mixed single particle size range (i.e. 90-4.5 mm). Nonetheless, the mixed single particle size range would very likely still exceed the limit values for NH_4^+ for all quality classes.

3.2.1 Valorization of the Inert fractions as substitute for construction aggregates

Due to the lack of an overarching ordinance in the EU regarding the recycling of construction materials and aggregates, the employment of the "Inert" fractions obtained from landfill-mined waste as a substitute for construction aggregates either falls into a relative grey area of waste legislation in many of the EU countries, or is subjected to ordinances for materials other than landfill-mined waste. For instance, in Austria the "Inert" fractions would need further treatment in order to be valorized as a substitute for construction aggregates according to the RBV. None of the particle size ranges 90-30 mm, 30-10 mm and 10-4.5 mm were strictly suitable for that type of valorization individually, which as previously mentioned would result more problematic than the valorization of these fractions as a mixed single particle size range 90-4.5 mm. Hence, the "Inert" fractions could be valorized as a mixed single particle size range in Austria, provided that they are further processed in a cleaning treatment. This treatment is to be designed in such a way that the amount of anionic surfactants and NH_4^+ are reduced and the limit values set in the RBV can be met. The content of NH_4^+ could be significantly reduced with the implementation of a nitrification process, while the amount of anionic surfactants could be decreased by a washing step. As the problematic parameters in the "Inert" fractions were not exceeded by high amounts, the further treatment of these fractions in order to meet the corresponding limit values seems technically possible: nonetheless, this might render the (E)LFM process economics unfavorable. Furthermore, the valorization of the inert fractions in (E)LFM projects is of critical importance, since they can account for a significant share of the fine fractions; such as in this case study, in which they represent 35.5 wt.% and 37.2 wt.% in the owc and dry states, respectively. Similarly to the combustible fractions, both the recovered inert fractions from the coarse fractions (i.e. the 3D >200 mm and 3D 200-90 mm fractions in the MSG case study) and the fine fractions are likely to be valorized together and, hence, the quality of the overall recovered inert fractions might be substantially improved in this manner, as the inert fractions recovered from the coarse fractions commonly show lower amounts of surface defilements and account for a significant share of the processed material.

It is also relevant to stress, that inert materials obtained through (E)LFM are not precisely included into the scope of the RBV and, therefore, their employment as recycled construction aggregates is not guaranteed even if all specifications have been met. Moreover, additional specifications for this type of valorization, which were not investigated in this study, may apply in the RBV. Therefore, suitable WtM schemes for the inert fractions recovered from the fine fractions of (E)LFM are to be further developed, while appropriate regulations need to be created at EU level.

4. CONCLUSIONS

The recovered "Combustibles" and "Inert" fractions from the fine fractions <90 mm of the MSG landfill case study corresponded to a material mainly composed of calorific fractions and a material constituted mostly by inorganic components, respectively. From an overarching perspective, the "Combustibles" fractions could be valorized as SRF in (co-)incineration, power and cement plants in the EU, under certain circumstances, since they meet the specifications established in the EN 15359:2011 in both the owc and dry states. These fractions could be valorized mixed in one single particle size range (i.e. 90-4.5 mm) in their original proportions or individually in particle size ranges (i.e. 90-30 mm, 30-10 mm and 10-4.5 mm). However, legislation on waste may vary from country to country in the EU and additional restrictions, as well as stricter limit values, can be applied in a specific member state. For example, in Austria these fractions can be incinerated, but not co-incinerated, according to the limit values for contaminants established in the AVV, as concentrations for As, Cd, Co, Hg and Pb were above the limit values in certain particle size ranges. In general, the quality of these fractions decreased with the decrease in particle size. As a mixed single particle size range only the concentrations of Cd, Hg and Pb exceeded the limit values.

In contrast to conventional (co-)incineration, the plasma gasification process proposed by the NEW-MINE project might offer an appealing WtE valorization route for the combustible fractions obtained from the fine fractions of landfill-mined waste, which in the present case study accounted for 12.5 wt.% and 9.0 wt.% of the total amount of the fine fractions in the owc and dry states, respectively. This valorization route could enable the upcycling of its residues into higher value-added products (e.g. glass-ceramics and inorganic polymers), in addition to the production of high quality energy carriers (e.g. hydrogen or methane): thus contributing to the economic and environmental feasibility of the project.

In Austria the "Inert" fractions would need further treatment in order to be valorized as a substitute for construction aggregates according to the RBV. None of the particle size ranges are strictly suitable for that type of valorization individually, as the contents of hydrocarbons, Cd, Pb, Zn, NH_4^+ and anionic surfactants were above the limit values. As it was the case for the "Combustibles" fractions, the quality of the "Inert" fractions decreased as particle size decreased. The valorization of these fractions as a mixed single particle size range would be less problematic than as individual particle size ranges, since the limit values of less parameters (i.e. hydrocarbons, Pb and NH_4^+) are expected to be exceeded in this way. Hence, the "Inert" fractions could be valorized as a mixed single particle size range in Austria, provided that they are further processed in a cleaning treatment. As the problematic parameters in this fraction were not exceeded by high amounts, the further treatment of these fractions in order to meet the corresponding limit values seems technically possible. Furthermore, the valorization of the inert fractions in (E)LFM projects is of critical importance, since they can account for a significant share of the fine fractions; such as in this case study, in which they represent 35.5 wt.% and 37.2 wt.% in the owc and dry states, respectively. Therefore, suitable WtM valorization schemes for the inert fractions recovered from the fine fractions of (E)LFM are to be further developed and appropriate overarching regulations need to be created at EU level.

It is important to emphasize that both the combustible and inert fractions recovered from the fine fractions are likely to be valorized together with those recovered from the coarse fractions in (E)LFM projects and, therefore, the overall quality of the resulting fractions might be improved in this way, as the fractions recovered from the coarse fractions frequently show better quality and account for a significant share of the processed landfill-mined material.

In general, impurities were associated to the presence of organic and inorganic pollutants and, thus, to a decrease on the valorization potential of both the “Combustibles” and “Inert” fractions. Although the dry state visually presented a lower amount of surface defilements than the owc state, to process these fractions in the dry state did not suffice to comply with the corresponding Austrian limit values. Therefore, cleaning methods would be needed to remove the contaminants from the “Combustibles” and “Inert” fractions in Austria. However, it seems unlikely that those methods will be economically feasible, as prices of primary raw materials and regulations remain to be daunting obstacles for (E)LFM. The increasing market prices of primary raw materials, the development of a holistic legal framework for secondary raw materials and the raising public awareness will set the conditions to justify further material and energy recovery from the fine fractions from (E)LFM, as well as the employment of innovative waste processing and cleaning technologies.

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11 MONT-SAINT-GUIBERT CASE STUDY: MECHANICAL PROCESSING AND CHARACTERIZATION OF THE FINE FRACTIONS <4.5 MM

Scientific article no. 10: “Case Study on Enhanced Landfill Mining at Mont-Saint-Guibert Landfill in Belgium: Mechanical Processing, Physico-Chemical and Mineralogical Characterisation of Fine Fractions <4.5 mm”

Vollprecht, D., **Hernández Parrodi, J.C.**, Lucas, H., Pomberger, R., 2020. Case Study on Enhanced Landfill Mining at Mont-Saint-Guibert Landfill in Belgium: Mechanical Processing, Physico-Chemical and Mineralogical Characterisation of Fine Fractions <4.5 mm. Detritus, In press. 10.31025/2611-4135/2020.13940.

Annotation on my personal contribution to this scientific article:

The tested approach of the mechanical processing applied to the fine fractions <4.5 mm was conceptualized by me in collaboration with Daniel Vollprecht, as well as the plan for the laboratory analyses. The mechanical processing was carried out by me and I prepared the samples for the laboratory analyses as well. The laboratory analyses for the pseudo-total contents and leaching contents were organized by me, while the mineralogical analyses were conducted by Daniel Vollprecht. I participated on the preparation of the article and was involved in the analysis and interpretation of the results. Also, I assisted in the review of the article.

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CASE STUDY ON ENHANCED LANDFILL MINING AT MONT-SAINT-GUIBERT LANDFILL IN BELGIUM: MECHANICAL PROCESSING, PHYSICO-CHEMICAL AND MINERALOGICAL CHARACTERISATION OF FINE FRACTIONS <4.5 MM

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ABSTRACT

Fine fractions obtained by mechanical processing of excavated waste constitute a challenge for (enhanced) landfill mining projects. These fractions are mainly composed of humified organic and weathered inorganic compounds, whereas metals and calorific fractions are depleted. In this study we present data on the chemical composition and grain size distribution of the fine fractions <4.5 mm, as well as on the mineralogical composition of the two finest subfractions (0.18 to 0.5 mm and <0.18 mm). Chemical analyses indicate no trend regarding the enrichment or depletion of heavy metals in the different particle size ranges. Leaching from the finer fractions is somewhat higher than from the coarser fractions (i.e. 1.6 to 4.5 mm and 0.5 to 1.6 mm), although the fraction 0.18 to 0.5 mm shows the lowest overall leaching. Pseudo-total contents of Cu, Zn, Cd, Hg and Pb and leachable contents of Ni exceed Austrian limit values for the production of soil substitutes from wastes. Electron microprobe analyses indicate that Zn and Pb, which exceed limit values for pseudo-total content, are present as Fe-Zn alloy, ZnS and $ZnSO_4$, and metallic Pb and Pb-Ca phosphate, respectively. In summary, dry-mechanical processing, which is a feasible method in the particle size range >4.5 mm, showed a limited effect in the range <4.5 mm. Removal of Pb- and Zn-containing phases is highly challenging due to the diverse mineralogy and fine grain size of few µm. Consequently, it seems unlikely that the Austrian limit values for soil substitutes can be met.

1. INTRODUCTION

Landfill mining, "a process for extracting […] resources from waste materials that have previously been disposed of […]" (Krook et al., 2012) was introduced in 1953 (Savage et al., 1993), whilst interest in this topic has increased significantly over the last 30 years. Although from an economic perspective landfill mining is largely not a feasible option (Laner et al., 2019), a combination of the process with environmental remediation may be promising (Frändgård et al., 2015), particularly when considering the value of ecosystem revitalisation (Bulakovs et al., 2017).

Fine fractions produced by mechanical processing of landfill mining materials are a major obstacle for an economically feasible (enhanced) landfill mining ((E)LFM) due to the predominant amounts and problematic characteristics (García López, et al., 2019; Hernández Parrodi, et al., 2019b; Hernández Parrodi, Höllen, & Pomberger, 2018a; Hernández Parrodi, Höllen, & Pomberger, 2018b).

Fine fractions have been considered a potential substrate for intermediate or final cover layers for both operational landfills or closed and excavated landfills, which may represent a source of revenue (Hogland, 2010; Greedy, 2016). A previous study from the Austrian LAMIS project indicates that the fine fraction <20 mm has a permeability of only 5.45 10^{-8} m/s, if it has been compacted to a density of 1.26 g/cm³ at an optimal water content of 23.2% and a temperature of 22°C (Liebetegger, 2015). Another option is use as soil substitute or construction aggregates (Spooren et al., 2013). For the latter application, the organic material should be removed from the fine fractions (Quaghebeur, et al., 2013), e.g. by physico-chemical treatment (Bhatnagar, et al., 2017).

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In the context of the NEW-MINE project a case study was conducted at Mont-Saint-Guibert (MSG) landfill in Belgium. Mechanical processing of the fine fractions 90 to 4.5 mm yielded median amounts of approx. 37.2 wt.% inert, 9.0 wt.% combustibles and 1.7 wt.% total metals in dry state of the total amount of fine fractions <90 mm (Hernández Parrodi et al., 2019c). In the latter case study, the extension of mechanical processing from a particle size of 10 mm to 4.5 mm increased the amount of recovered materials by around 10 wt.% (Hernández Parrodi et al., 2019c), thus representing an additional amount of resource potential in comparison with previous studies in which particle sizes below 10 mm were not processed (Wanka, Münnich, & Fricke, 2017). However, fine fractions <4.5 mm which, due to their fine grain size are not suitable for separation either manually or using sensor-based technologies, remain highly challenging (Küppers, et al., 2019). Direct sorting technologies such as magnetic and eddy-current separation may be applied in the recovery of ferrous and non-ferrous metals, respectively, down to a particle size of 4.5 mm (Hernández Parrodi et al., 2019c; Lucas et al., 2019); however, these materials only account for a small amount of the total quantity of fine fractions, leaving behind a large share of fine fractions <4.5 mm – composed mainly of weathered inorganic and decomposed organic matter (Hernández Parrodi, et al., 2019a).

In view of the characteristics of the fine fractions <4.5 mm, being a mixture of organic compounds and mineral phases, utilisation as a soil substitute has been discussed (Hernández Parrodi, Höllen, & Pomberger, 2018b; Hernández Parrodi et al., 2019c). Soils have been defined as the uppermost biologically active part of the Earth´s crust, contributing to promoting soil functions (Scheffer & Schachtschabel, 2018). Soil sealing leads to a loss of these functions, thus constituting a major environmental concern (Scalenghe & Marsan, 2009). Additionally, approx. 25 million tons of excavated soils are landfilled in Austria every year (Federal Ministry for Sustainability and Tourism, 2017). Consequently, to maintain soil functions, soil substitute materials (Federal Ministry for Sustainability and Tourism, 2017) are produced for recultivation purposes. In Austria, legal requirements dictate the production of soil substitutes from waste, particularly to prevent recirculation of contaminants (Austrian Standards, 2013).

The fine fractions <4.5 mm of landfill mining materials are rich in both organic and inorganic contaminants compared to the bulk of excavated materials (Burlakovs et al., 2016). Results of tests conducted on these fractions show how most of the potentially toxic elements studied (As, Ba, Cd, Co, Cr, Cu, Fe, Mg, Mn, Ni, Pb, Sb and Zn) were bound to fractions of low extractability. This suggests that the fraction could be used as a low-risk cover material during environmental site remediation, landfill recultivation and land restoration, although further environmental analysis should first be performed due to the low mobility and leaching potential of toxic metals. In several countries total contents may also be used as limit values for the recycling of wastes inhibiting the utilization of wastes even at low leachability. A Swedish study reported how the total contents of zinc (Zn), barium (Ba) and chromium (Cr) in fine fractions of landfilled material were above threshold values for contaminated soil (Jani et al., 2016). In this context, it should be considered that many metals may not only pose a threat to the environment, but also contribute to the resource potential of fine fractions (Burlakovs et al., 2018). An additional concern is associated with the presence of organic carbon, which may lead to the formation of methane (Mönkäre, Palmroth & Rintala, 2016). Thus, utilization of the entire fine fractions <4.5 mm for protection of natural resources might contradict the aim of waste management to protect human health and the environment by removing contaminants from a circular economy (Republic of Austria, 2002).

Consequently, to achieve all three aims of waste management, i.e. protection of human health, protection of the environment and protection of natural resources, separation of fine fractions <4.5 mm into a contaminant-depleted fraction for recycling as soil substitute and a contaminant-enriched fraction for disposal at a sanitary landfill is mandatory.

Advanced separation technologies for grain size ranges below 4.5 mm are state-of-the-art in mineral processing, e.g. flotation (Peleka, Gallios, & Matis, 2017), electrostatic separation (Kelly & Spottiswood, 1989) or selective leaching of individual mineral phases (Lane et al., 2016), although detailed knowledge of the phase composition of the material is required. Due to the frequent lack of relevant information with regard to fine fractions from landfill mining, often also associated with significantly higher costs, this study tested a more simple approach, i.e. the screening and dry abrasion of surface defilements (i.e. impurities).

The first working hypothesis for this treatment was based on the knowledge that contaminants are enriched in the finest fraction, thus implying that even in the range <4.5 mm separation between a clean coarser fraction and a contaminated finer fraction might be achieved.

The second working hypothesis referred to mobility of contaminants in the fine fraction: Although fine fractions of landfill mining materials are often described as soil-like material (Hernández Parrodi, Höllen, & Pomberger, 2018b; Hernández Parrodi et al., 2019c) no studies have been conducted to date to assess their mineralogical composition. However, detailed knowledge is not only necessary for advanced separation technologies, but also to gain a deeper understanding of the leachability of heavy metals related to their mineral host phases (Vollprecht, et al., 2019). Existing studies on the mobility of contaminants from LFM fine fractions (Burlakovs, et al., 2016) follow the approach of sequential extraction, but do not explicitly address mineralogy of the fine fraction.

Consequently, our second hypothesis suggests that the mineralogy of (E)LFM fine fractions is related to leachability, as is the case for other materials such as slags (Neuhold, et al., 2019) and rocks (Vollprecht, et al., 2019).

To summarise, we present here the first study of fine fractions from landfill mining, including a comprehensive mineralogical analysis with particular emphasis on inorganic contaminants present and related leaching behaviour.

2. MATERIALS AND METHODS

2.1 Materials

Fine fractions <4.5 mm were obtained from mechanical processing of fine fractions <90 mm from MSG landfill, Belgium, performed by Hernández Parrodi et al., 2019c (Figure 1). Fractions were produced after sieving composite samples of batches 1 and 2 of fine fractions <90 mm; first at 30 mm, subsequently at 10 mm and finally at 4.5 mm at optimal water content (15 wt.%) and in dry state. Additionally, particles ranging from 90 to 30 mm, 30 to 10 mm and 10 to 4.5 mm were sieved once more at 4.5 mm after a series of mechanical processing steps (i.e. extraction of ferrous and non-ferrous metals, density separation and sensor-based sorting), with the purpose of removing released surface defilements. The subsequently produced fractions <4.5 mm were combined with fine fractions <4.5 mm for further handling. Total amount of fine fractions <4.5 mm corresponded to 42.9 wt.% and 42.7 wt.% of fine fractions <90 mm at optimal water content and in dry state, respectively (Hernández Parrodi et al., 2019c). In turn, the fine fractions <90 mm accounted for approx. 77 wt.% of the total amount of processed material in raw state from the MSG landfill (Hernández Parrodi et al., 2019a). Additional details on the fine fractions <90 mm and mechanical processing, as well as further information about the sampling method and preparation of composite samples, are reported in Hernández Parrodi et al., 2019a and Hernández Parrodi et al., 2019c.

A total of six composite laboratory samples (n=6), containing both batch 1 and batch 2, were obtained from composite samples of the fine fractions <4.5 mm at optimal water content (n=3) and in dry (n=3) state, and the physico-chemical properties determined. In line with the properties detected and the findings of the study on particle size distribution and water content in the fine fractions <90 mm performed by Hernández Parrodi et al., 2019c, additional mechanical processing of the fine fractions <4.5 mm was designed. The study of particle size distribution and water content revealed that in order to achieve adequate particle size classification of the fine fractions below 3 mm, further reduction of the water content is needed, particularly below 0.6 mm. Therefore, only composite samples of batches 1 and 2 of the fine fractions <4.5 mm in dry state were used for further mechanical processing. This suggests that the composite samples at optimal water content state would need to be dried and processed in the mechanical processing. It is important to note that the state referred to as "the dry state" does not correspond to a strictly dry state, but rather to an average water content of 1.5 wt.% due to absorption/adsorption of ambient moisture by the material throughout the whole mechanical processing.

Additionally, six soil samples were taken from the landfill and the surrounding area for comparison of determined heavy metal concentrations with geological background concentrations.

2.2 Mechanical Processing

The fine fractions <4.5 mm were subjected to dry-mechanical processing consisting of particle size classification steps (i.e. sieving), followed by a surface cleaning process, driven by superficial erosion (surface attrition), and a second particle size classification step for elimination of loosened surface defilements and detritus. Figure 2 displays a graphic representation of the dry-mechanical processing applied.

A total of eight composite samples (n=8) of the fine fractions <4.5 mm of batch 1 (n=4) and batch 2 (n=4) in dry state were sieved further into four particle size ranges (i.e. 4.5 to 1.6 mm, 1.6 to 0.5 mm, 0.5 to 0.18 mm and <0.18 mm). The samples subsequently underwent chemical analysis to identify the particle size range(s) featuring

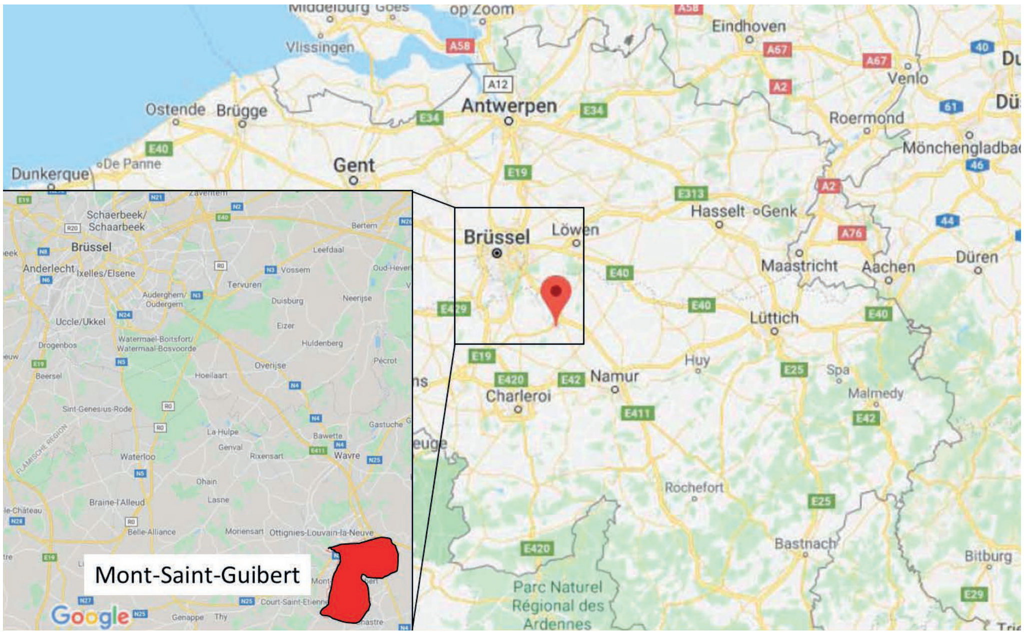

FIGURE 1: Location of the Mont-Saint-Guibert landfill.

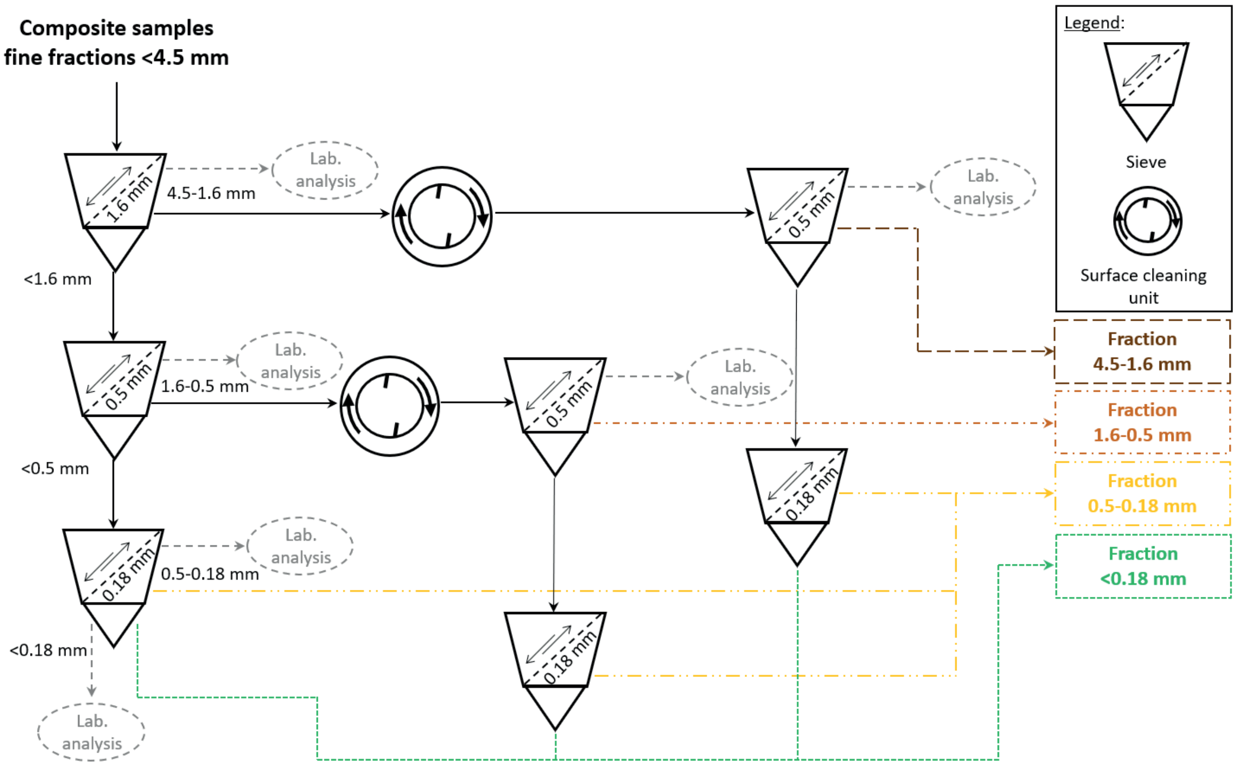

FIGURE 2: Scheme of dry-mechanical processing of the fine fractions <4.5 mm.

the highest concentrations of pollutants and to determine whether the quality of fine fractions <4.5 mm could be improved through further mechanical processing. For this purpose, composite samples were further sieved in a vibratory sieve tower (Retsch AS 200) with woven wire test sieves and squared openings of 1.6 mm, 0.5 mm and 0.18 mm at an amplitude of 100%. Due to the amount of material, prior to sieving, each composite sample was divided into two or three subsamples. Each subsample was sieved for 1 minute to simulate an industrial sieving process, and the amounts of all particle size ranges determined using a precision scale (Sartorius ENTRIS6202-1S; resolution of 0.01 g). After sieving, three composite samples (n=3) were used to determine the physico-chemical properties of each of the four particle size ranges produced. In turn, four composite samples (n=4), including both batch 1 and batch 2, for each of the particle size ranges 4.5 to 1.6 mm and 1.6 to 0.5 mm (n=8) were further mechanically processed by surface cleaning. For this purpose, the particle size ranges 4.5 to 1.6 mm and 1.6 to 0.5 mm underwent further processing in a surface cleaning unit, which consisted of an automatic concrete mixer (Atika BM 125 S) rotated at a speed of 30 rpm with an inclination of 45° for 10 minutes for each composite sample (Figure 3). The objective of the surface cleaning process was to decrease the concentration of pollutants in the coarser particle size ranges (i.e. 4.5 to 1.6 mm and 1.6 to 0.5 mm), since it was assumed that the majority of pollutants would be present in the finer particle size ranges (0.5 to 0.18 mm and <0.18 mm), which would attach to the surface of the coarser particle size ranges as surface defilements.

One composite sample from each set of four was stored for future use in additional laboratory analyses or alternative processing steps. As shown in Figure 2, a dry surface cleaning process was followed by 1-minute sieving at 0.5 mm and 0.18 mm using the previously described vibrating sieve. Finally, the obtained composite samples were used to determine the physico-chemical properties of fractions subjected to the surface cleaning process, with the aim of analysing and evaluating effectiveness and performance.

2.3 Chemical Analyses

Three of the composite samples <4.5 mm were analysed for chemical composition (20 oxides) by means of X-ray fluorescence (XRF) spectrometry using fusion tablets according to DIN EN ISO 12667 at CRB GmbH, Hardegsen, Germany. Loss of ignition (LOI) was determined according to DIN EN ISO 26845 at 1025°C. The mean value of the three analyses was used for further considerations.

Three composite samples of each of the fractions 4.5 to 1.6 mm, 1.6 to 0.5 mm, 0.5 to 0.18 mm and <0.18 mm (n=12) were chemically analysed at the laboratory of the Chair of Waste Processing Technology and Waste Management (AVAW) of the Montanuniversität Leoben. Additionally, the chemical composition of three composite samples of each of the fractions 4.5 to 1.6 mm and 1.6 to 0.5 mm (n=6) was determined subsequent to dry surface cleaning to compare the concentrations of different pollutants prior to and following dry surface cleaning.

Chemical analyses were generally conducted according to ÖNORM S 2122 ("Soils from Wastes"), which was also taken as a basis for reference values of different parame-

FIGURE 3: Scheme of dry-mechanical processing of the fine fractions <4.5 mm.

ters to be complied with. Additionally, as no limit values for pseudo-total contents (aqua regia digestion) are provided in ÖNORM S2122, limit values for pseudo-total contents of contaminants for excavated soil landfills (Federal Ministry for Agriculture, Forestry, Environment and Water Management, 2008) and recycling of excavated soil (Federal Ministry for Sustainability and Tourism, 2017) were used for comparison. Samples were analysed for total carbon (TC), total organic carbon (TOC, both according to EN 13137), nitrogen (N), adsorbable organic halogens (AOX, according to DIN 38414-18), polycyclic aromatic hydrocarbons (PAHs, according to ÖNORM L 1200), polychlorinated biphenyls (PCBs, according to DIN 38414-20), the cohesion number (KH value, according to ÖNORM S2122-2) and the hydrocarbon index (according to ÖNORM EN 14039). TOC/N ratio was calculated according to ÖNORM S 2122-2. Furthermore, physical properties, including dry and wet density (ÖNORM S 2122-1) and water content (according to ÖNORM L 1062), were determined.

For the determination of pseudo-total metal content, samples were digested in aqua regia according to ÖNORM EN 13657. Metals were determined in the digested sample by means of inductively coupled plasma mass spectrometry (ICP-MS) according to ÖNORM EN ISO 17294-2.

Water-soluble constituents were determined according to ÖNORM L 1092 and ÖNORM S 2122-1. As the production of a saturated water extract was not possible, the following procedure was applied: 100 g air-dried sample was suspended in 500 g pure water and shaken for 2 h in an overhead shaker. Solids were separated from the solution by a centrifuge (15 min at 5,500 rotations per min) and subsequent filtration (0.45 µm). The resulting leachates were analysed for pH (according to ISO 10523), electric conductivity (according to DIN EN 27888), permanganate index (C_{ox}, according to ÖNORM EN ISO 8467), dissolved organic carbon (DOC, according to ÖNORM EN 1484), anions (i.e. fluoride, chloride, nitrate, sulphate and phosphate, according to DIN EN ISO 10304-1), ammonium (according to DIN 38406-5) and other cations (according to ÖNORM EN ISO 17294-2). Three composite samples (n=3) were analysed for each parameter and the arithmetic mean, together with the standard error (confidence interval of 95%), were calculated based on the results of laboratory analysis.

Finally, the six soil samples obtained from the landfill and surrounding areas were analysed for Ba, Ge, Cd, Cr, Co, Cu, Ge, As, Hf, Sc, Li, Au, Ag by means of inductively coupled plasma optical emission spectrometry (ICP-OES) at the Chair of Process Metallurgy and Metal Recycling at RWTH Aachen University. Furthermore, S and C were determined in the same laboratory by combustion and subsequent determination of oxides in the off-gas.

2.4 Mineralogical Analyses

Modal mineral composition of the fractions <0.18 mm and 0.18 to 1.5 mm from batch 1 and batch 2 was investigated by means of X-ray powder diffraction (XRD) analysis. Two powdered samples (n=2) of each particle size range and batch were analysed using a PANalytical X'Pert Pro diffraction instrument (CoKα radiation (λ=1.79 Å)), 40 mA, 45 kV) and PANalytical HighScore Plus software package at the Institute of Applied Geosciences, Graz University of Technology. Diffractograms were automatically quantified using Rietveld refinement. Resulting net lower limits of detection were in the order of 2 - 5 wt.%, indicating the potential presence of minerals at lower concentrations, although not detectable by XRD.

The distribution of C, S, Pb, Si, Cu, Al, O, K, Ca, P, Zn, Na, Mg, Ba and Fe was determined for the same samples by electron probe microanalyses (EPMA) using the JEOL JXA 8200 instrument installed at the Chair of Resource Mineralogy, Montanuniversität Leoben. Polished sections were carbon coated (EMITECH K950X) to minimize charging under the electron beam. Element maps of mineral phases were conducted using wavelength-dispersive spectrometers (WDX). Heavy-metal containing phases were qualitatively analysed for chemical composition using energy dispersive spectrometers (EDX). The instrument was operated in high vacuum (<1.65 10^{-5} mbar), with 15 kV acceleration voltage, 10 nA beam current (on Faraday cup), and with beam diameter set to spot size (»1 µm).

3. RESULTS AND DISCUSSION

3.1 Mechanical Processing

As described in Section 2 all composite samples of the fine fractions <4.5 mm in the dry state were initially sieved at 1.6 mm, 0.5 mm and 0.18 mm. Half of the resulting composite samples of particle size ranges 4.5 to 1.6 mm, 1.6 to 0.5 mm, 0.5 to 0.18 mm and <0.18 mm were used to determine the physico-chemical properties of fractions prior to the surface cleaning process. This process was undertaken to assess whether enrichment of any of the studied parameters, such as heavy metals, PAHs and PCBs, among others, occurred in the presence of any specific particle size distribution and, thus determine whether the same parameters could be concentrated in a certain particle size range by means of particle size classification. Additionally, the physico-chemical characteristics of each particle size range were used as a reference to evaluate the effects of the surface cleaning process. Figure 4 displays the general mass balance of the mechanical processing approach studied in this investigation. Figures for the general mass balance were calculated using the arithmetic mean of the four composite samples (n=4) processed in the tested mechanical processing, based on the average amount of fine fractions <4.5 mm (42.9 wt.%) versus the total quantity of fine fractions <90 mm processed in dry state in our previous study (Hernández Parrodi et al., 2019c).

The general mass balance in Figure 4 revealed amounts corresponding to approx. 13.9 wt.%, 10.8 wt.%, 12.7 wt.% and 5.6 wt.% for the particle size ranges 4.5 to 1.6 mm, 1.6 to 0.5 mm, 0.5 to 0.18 mm and <0.18 mm, respectively. This highlighted a tendency of the amount of material to decrease in line with reduction in particle size, with the exception of particle size range 0.5 mm to 0.18 mm, featuring a higher amount than the particle size range 1.6 mm to 0.5 mm. Images of the obtained fractions are shown in Figure 5.

Directly after the initial sieving steps at 1.6 mm, 0.5 mm and 0.18 mm, composite samples of particle size ranges 4.5 mm to 1.6 mm and 1.6 mm to 0.5 mm were processed in the surface cleaning unit and subsequently sieved at 0.5 mm and 0.18 mm. An average material loss of approx. 1.2 wt.% due to surface cleaning and subsequent sieving was estimated, whereas an amount of about 3.4 wt.% of liberated surface defilements and detritus after the surface cleaning process was calculated, compared to the total amount of fine fractions <90 mm processed in the dry state. As only a modest average water content of 1.5 wt.% (Table 4) was determined in the processed composite samples, further influence of ambient moisture was deemed negligible in regards to general mass balance. Respective amounts of 0.9 wt.% and 0.7 wt.% of the fraction 0.5 mm to 0.18 mm were obtained in particle size ranges 4.5 mm to 1.6 mm and 1.6 mm to 0.5 mm after sieving at 0.18 mm, while quantities of 1.3 wt.% and 0.6 wt.% of the fraction <0.18 mm were yielded, respectively. Therefore, the dry-mechanical processing used in this study produced total amounts of approx. 11.7 wt.% fine fractions 4.5 mm to 1.6 mm (clean), 9.5 wt.% fine

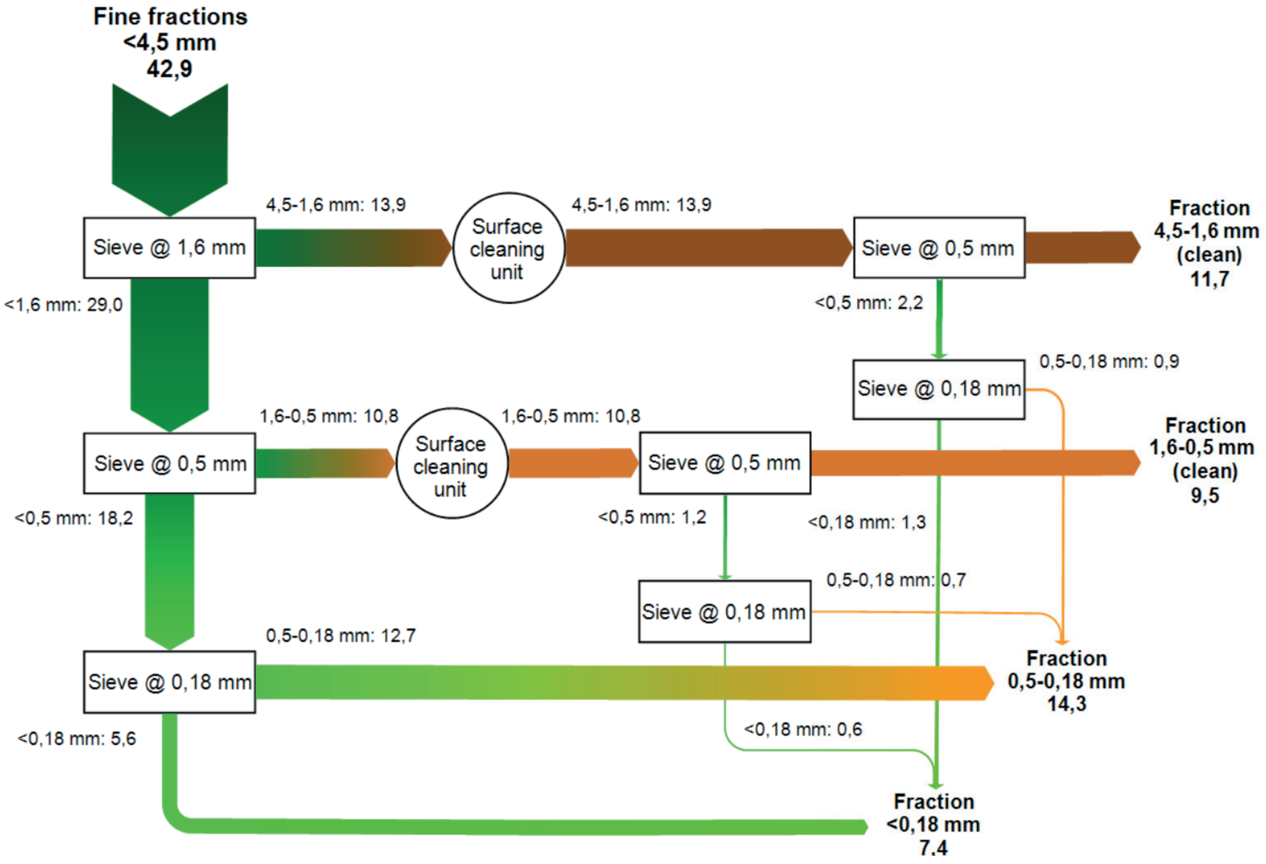

FIGURE 4: General mass balance of the mechanical processing of the fine fractions <4.5 mm, figures in wt.%.

fractions 1.6 mm to 0.5 mm (clean), 14.3 wt.% fine fractions 0.5 mm to 0.18 mm and 7.4 wt.% fine fractions <0.18 mm. Images of the coarser particle size ranges 4.5-1.6 mm and 1.6-0.5 mm after the dry surface cleaning process and subsequent sieving at 0.5 mm and 0.18 mm are shown in Figure 6.

3.2 Chemical Analyses

The chemical composition of the entire fine fraction <4.5 mm is displayed in Table 1. SiO_2 represented the main chemical component at approx. 70 wt.%, followed by LOI (14 wt.%), CaO (5 wt.%), Fe_2O_3 and Al_2O_3 (each 4 wt.%). All other analysed chemical components were below 1 wt.%. Compared to the average composition of the Earth´s Crust (Taylor, 1964), samples were rich in SiO_2, but depleted in Al_2O_3. This suggests that either SiO_2-enriched materials, e.g. building sand, had been landfilled, or that SiO_2 had become enriched following deposition in the landfill. However, usually due to weathering, not only SiO_2, but also Al_2O_3 are found to be enriched, thus supporting the first hypothesis, i.e. landfilling of SiO_2-enriched materials.

Pseudo-total contents of chemical elements in the investigated samples are summarized in Table 2. The pseudo-total contents of almost all elements in the fraction 0.5 to 0.18 mm corresponded to approximately half the values obtained from the coarser (1.6 to 0.5 mm and 4.5 to 1.6

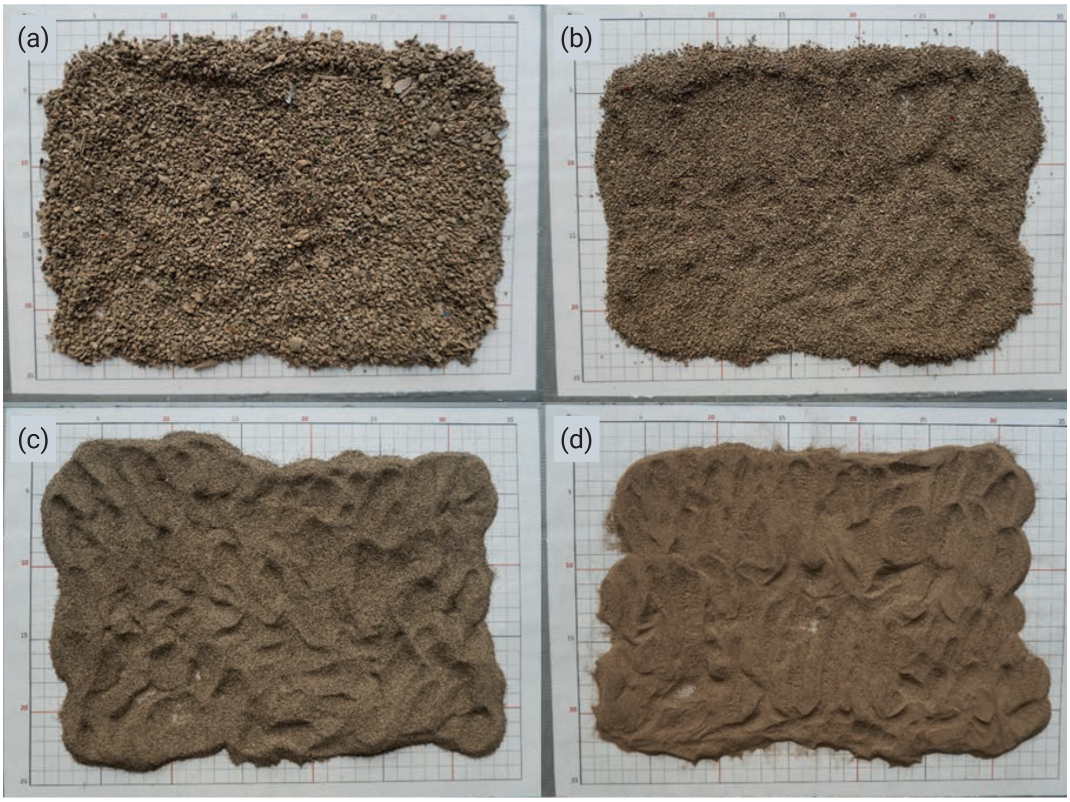

FIGURE 5: Particle size ranges (a) 4.5 to 1.6 mm, (b) 1.6 to 0.5 mm, (c) 0.5 to 0.18 mm and (d) <0.18 mm of the fine fractions <4.5mm after first sieving steps.

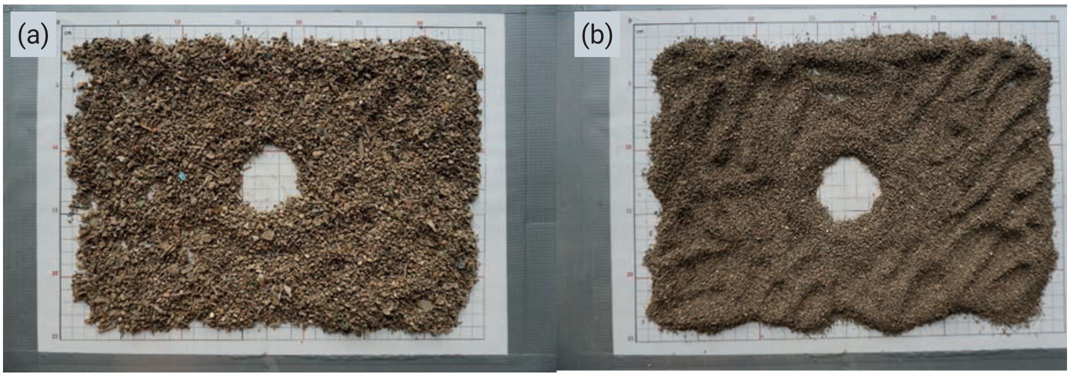

FIGURE 6: Particle size ranges (a) 4.5 to 1.6 mm and (b) 1.6 to 0.5 mm of the fine fractions <4.5 mm after the dry surface cleaning process and second sieving step.

TABLE 1: Chemical composition (fusion tablet, data refer to dry matter (DM)) of the fine fractions < 4.5 mm.

Parameter	Unit	<4.5 mm_1	<4.5 mm_2	<4.5 mm_3	Mean
SiO_2	wt.%	69.37	70.01	69.80	69.73
Al_2O_3	wt.%	4.00	3.98	4.00	3.99
Fe_2O_3	wt.%	4.52	4.41	4.48	4.47
Cr_2O_3	wt.%	0.01	0.01	0.01	0.01
MnO	wt.%	0.04	0.04	0.04	0.04
TiO_2	wt.%	0.28	0.28	0.29	0.28
V_2O_5	wt.%	0.01	0.01	0.01	0.01
P_2O_5	wt.%	0.24	0.24	0.23	0.23
CaO	wt.%	4.90	4.76	4.85	4.84
MgO	wt.%	0.62	0.61	0.63	0.62
K_2O	wt.%	0.79	0.79	0.83	0.80
Na_2O	wt.%	0.37	0.38	0.38	0.38
SO_3	wt.%	0.82	0.71	0.83	0.79
ZrO_2	wt.%	0.02	0.02	0.02	0.02
NiO	wt.%	0.01	0.01	0.01	0.01
CuO	wt.%	0.02	0.03	0.02	0.02
ZnO	wt.%	0.11	0.11	0.11	0.11
Rb_2O	wt.%	0.01	0.01	0.01	0.01
SrO	wt.%	0.02	0.02	0.02	0.02
BaO	wt.%	0.06	0.06	0.07	0.06
LOI	wt.%	13.72	13.47	13.32	13.50
Sum	wt.%	99.92	99.92	99.91	99.92

mm) and finer (<0.18 mm) fractions. The sum of all analytes accounts for 5.8 wt.% of the fraction 0.5 to 0.18 mm and 9.9 to 12.6 wt.% for the three other fractions. This can be explained by different dissolution behaviour of this fraction during aqua regia digestion. Silicon concentrations were below 0.1 wt.% for all fractions, although SiO_2 concentrations were about 70 wt.% according to XRF, in agreement with the fact that aqua regia does not dissolve silicate minerals. Consequently, it is suggested that the fraction 0.5 to 0.18 mm may be richer in silicate minerals. Considering the lack of oxygen analyses, it can be estimated that approx. 85 wt.% of the samples (exceeding 90% wt for the fraction 0.5 to 0.18 mm) are made up of silicates.

The main constituents were found to be Ca (2.4 wt.% in the fraction 0.5 to 0.18 mm, 4.4-4.8 wt.% in the other fractions), Fe (1.9 wt.% in the fraction 0.5 to 0.18 mm, 3.2 wt.% in the fraction <0.18 mm and 4.8-5.0 wt.% in the coarser fractions) and Al (0.7 wt.% in the fraction 0.5 to 0.18 mm, 1.1-1.3 wt.% in the other fractions). All other elements were below 1 wt.%. Ca and Fe concentrations substantially matched the results obtained by XRF, whereas Al concentrations were significantly lower in digested samples compared to XRF measurements. This suggests that Al is bound to silicate minerals, whereas Ca and Fe are bound to more soluble phases such as carbonates and hydroxides, respectively.

The recycling of fine fractions from ELFM as soil substitute is not directly regulated in Austria. Soil substitutes may only be produced from a restricted list of wastes including excavated soil, but not specifically including (E)LFM materials. However, due to the soil-like character of the material, limit values for the recycling of excavated soil (Federal Ministry for Sustainability and Tourism, 2017) as soil substitute might be used as an approximation. Furthermore, limit values for excavated soil landfills (Federal Ministry for Agriculture, Forestry, Environment and Water Management, 2008), which are almost identical to limit values established for recycling, thus further supporting the need to assess environmental impact of the investigated material. Both these limit values and also concentrations detected refer to pseudo-total content obtained by aqua regia digestion.

In general, the pseudo-total contents of contaminants were in the same range as those observed for the Kudjape landfill, Latvia (Burlakovs et al., 2016). A comparison between determined values and limit values shows that pseudo-total contents of Cr, Co, As and Ni were below the limit values for all fractions, whereas determined values for Cu, Zn, Cd, Hg and Pb were above the limit values for all fractions (except Hg for the fraction 0.5 to 0.18 mm). This may imply either that Cr, As, Co and Ni are only present in very low concentrations or that they are bound to the silicates or other low-soluble phases such as oxides. In the case of As, present as oxyanion, also strong sorption in the acidic pH might play a role, as the mineral surfaces are charged positively in this pH range. Conversely, Cu, Zn, Cd, Hg and Pb represent chalcophilic elements, which are instead bound to sulphide minerals. Under oxidizing conditions, such as in aqua regia, these are easily dissolved. This suggests that this group of elements may be increasingly bound to sulphides or similar mineral phases, or adsorbed on surfaces of mineral or organic matter.

No trend was observed with regard to the enrichment or depletion of heavy metals in the different particle size ranges. This indicates the unsuitability of particle size classification in the range <4.5 mm as a means of achieving limit values for pseudo-total content of heavy metals in the investigated ELFM fine fractions. As certain heavy metals (e.g. Cd and Pb) are frequently present in glass products (especially in the past), and glass was not sorted out of these fractions, these elements might be bound to glass. Glass separation, e.g. by density separation, might represent a means of decreasing the content of these elements.

Furthermore, background concentrations of heavy metals in soil at the landfill site and surrounding areas should also be taken into account (Table 3), specifically to determine the extent to which the heavy metal concentrations should be attributed exclusively to waste disposed of at the landfill, and thus enable a conclusive assessment of heavy metal concentrations. Both investigated heavy metals and carbon content were below the limit value for excavated soil landfills in Austria (Federal Ministry for Agriculture, Forestry, Environment and Water Management, 2008). Consequently, the geogenic background concentration may be considered negligible.

In addition to heavy metals, organic contaminants were also found to partly exceed limit values for excavated soil landfills and recycling (Table 4). This was indeed the

TABLE 2: Pseudo-total contents of the investigated fine fractions (n=3, s=1σ), bold parameters are above threshold values, comparable data from Burlakovs et al (2016), limit values for excavated soil landfills according to (Federal Ministry for Agriculture, Forestry, Environment and Water Management, 2008), for recycling quality class BA according to (Federal Ministry for Sustainability and Tourism, 2017).

Parameter	Unit	4.5-1.6 mm	1.6-0.5 mm	0.5-0.18 mm	<0.18 mm	Burlakovs et al (2016)	Limit value for excavated soil landfills	Limit value for recycling (class BA)
Li	mg/kg DM	11±0	11±0	5±0	9±1		-	
Be	mg/kg DM	<10	<10	<10	<10		-	
B	mg/kg DM	32±2	36±2	17±2	26±2		-	
Na	mg/kg DM	747±75	827±69	347±17	587±57		-	
Mg	mg/kg DM	4867±173	4953±141	2263±154	3540±93	8700 - 10200	-	
Al	mg/kg DM	10567±962	12767±736	7310±1435	11167±728		-	
Si	mg/kg DM	770±317	977±105	630±88	507±133		-	
P	mg/kg DM	1353±112	1413±92	637±52	1080±97		-	
K	mg/kg DM	2187±107	2390±131	1370±57	2683±159		-	
Ca	mg/kg DM	44067±3437	47867±131	23933±10178	44500±9061		-	
Ti	mg/kg DM	210±20	223±17	117±7	217±17		-	
V	mg/kg DM	27±8	29±3	15±3	28±3		-	
Cr	mg/kg DM	96±17	107±7	45±4	76±0	54 - 123	300	300
Mn	mg/kg DM	477±66	510±11	197±24	323±29	313 - 383	-	
Fe	mg/kg DM	48300±7355	49867±3927	19400±2012	31633±1829	29600 - 53900	-	
Co	mg/kg DM	13±1	15±1	5±0	10±0	6 - 8	50	50
Ni	mg/kg DM	74±1	95±17	41±7	69±19	29 - 44	100	100
Cu	**mg/kg DM**	**770±663**	**430±137**	**133±7**	**197±13**	**191 - 362**	**100**	**100**
Zn	**mg/kg DM**	**1203±125**	**1260±147**	**567±36**	**953±79**	**1300 - 2000**	**500**	**500**
As	mg/kg DM	12±1	14±1	<10	12±1	4 - 6	50	50
Se	mg/kg DM	<10	<10	<10	<10		-	
Sr	mg/kg DM	150±11	167±7	86±2	153±7	120 - 479	-	
Mo	mg/kg DM	9±3	12±4	3±0	5±1		-	
Pd	mg/kg DM	<1	<1	<1	<1		-	
Ag	mg/kg DM	5±2	6±3	2±1	4±1		-	
Cd	**mg/kg DM**	**5±1**	**7±1**	**3±0**	**5±1**	**1**	**2**	**2**
Sn	mg/kg DM	220±60	293±46	106±13	177±24		-	
Sb	mg/kg DM	8±1	12±2	5±0	8±2		-	
Te	mg/kg DM	<2	<2	<2	<2		-	
Ba	mg/kg DM	663±68	763±73	350±49	577±51	246 - 420	-	
W	mg/kg DM	17±3	16±2	<1	<1		-	
Hg	**mg/kg DM**	**6±0**	**1±0**	**<1**	**2±0**		**-**	**1**
Tl	mg/kg DM	<1	<1	<1	<1		-	
Pb	**mg/kg DM**	**670±23**	**1010±122**	**460±57**	**777±86**	**128 - 477**	**150**	**150**

case for TOC, hydrocarbon index and PAH, whereas PCB remained below limit values. Compared to ranges established by ÖNORM S 2122-2, the TOC/N ratio was rather high, although TOC was within established limits. Differences between legislations may be explained by the fact that in soils organic carbon is mainly present as humic substances which represent stable forms or carbon, whereas in organic wastes instable forms such as carbohydrates, proteins and lipids are present, which tend to form methane under anaerobic conditions in landfills. Ecological evaluation of use of the investigated samples as soil substitute, both degree of humification, i.e. the conversion of instable to stable organic substances in the material, and redox regime in the planned application should be considered.

3.3 Leaching Behaviour

Water soluble constituents are displayed in Table 5. These constituents were determined using a liquid: solid ratio of 5:1 over a 2 h period to compare soluble concentrations to recommended values for regular soil according to ÖNORM S 2122-2. However, limit values for landfilling and recycling relate to a liquid: solid ratio of 10 and leaching

TABLE 3: Geogenic background concentrations of selected chemical elements (bdl: below detection limit).

Parameter / Unit	Ba	Ge	Cd	Cr	Co	Cu	Ga	As	Hf	Sc	Li	Au	C	S
Sample	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**ppm**	**wt.%**	**wt.%**
1	188	bdl	bdl	158	18	14	bdl	11	bdl	92	134	45	0.08	0.012
2	367	bdl	2	67	13	14	bdl	9	bdl	34	128	39	1.15	0.027
3	198	bdl	bdl	72	12	15	bdl	9	bdl	30	118	28	0.85	0.021
4	377	bdl	bdl	143	13	14	bdl	7	bdl	33	128	32	0.82	0.020
5	224	bdl	bdl	83	11	10	bdl	5	bdl	30	117	28	0.42	0.011
6	194	bdl	2	84	12	9	bdl	8	bdl	29	115	29	0.32	0.016

TABLE 4: Physical and chemical parameters of the investigated fine fractions (n=3, s=1σ), bold parameters are above threshold values, limit values for excavated soil landfills according to Federal Ministry for Agriculture, Forestry, Environment and Water Management (2008), for recycling quality class BA according to Federal Ministry for Sustainability and Tourism (2017).

Parameter	Unit	4.5-1.6 mm	1.6-0.5 mm	0.5-0.18 mm	<0.18 mm	Ranges according to ÖNORM S2122-2	Limit value for excavated soil landfills	Limit value for recycling (class BA)
AOX	mg/kg DM	255	285	218	293			
Cohesion number	1	71.40	87.60	54.37	61.10	41 - 90		
Wet density	g/cm³	0.72	0.74	1.09	0.95			
Dry density	g/cm³	0.71	0.72	1.08	0.94			
TOC	**% C DM**	**8.31**	**8.04**	**7.91**	**7.72**	**1.5-11.6**	**3.00**	**1.00**
Total-N	% DM	0.49	0.53	0.27	0.34			
C	% DM	9.95	10.80	10.16	10.38			
TOC/N	**1**	**17.83**	**15.20**	**28.93**	**22.83**	**9-14**		
Hydrocarbon index	**mg/kg DM**	**980**	**1,233**	**507**	**967**		**200**	**200**
PAH (16/EPA)	**mg/kg DM**	**17.80**	**17.73**	**6.38**	**7.68**		**4**	**4**
Polychlorinated biphenyles	mg/kg DM	0.33	0.47	<0.10	0.40			1
Water content (105 °)	wt.%	1.57	1.80	0.80	1.53		-	-

time of 24 h. Thus, no direct comparison is possible. However, in order to assess the mobility of chemical elements, a comparison with all three groups of values provides some orientation.

Electric conductivity of the leachate was lowest for the fraction 0.5 to 0.18 mm. This corresponds to the observation of the lowest solubility of this fraction in aqua regia, thus suggesting that the fraction is not only richer in silicates, but also in mineral phases which are soluble in aqua regia, but insoluble in water. In contrast to the observations made in aqua regia, for water extraction the finest fraction displayed a significantly higher percentage of soluble elements than other fractions. With the exception of fraction 0.5 to 0.18 mm, a general trend of increasing solubility with decreasing particle size was detected, likely caused by an increased surface area.

Generally speaking, and in agreement with the findings of a previous study (Burlakovs et al., 2016), the share of water soluble contaminants was approx. three orders of magnitude lower than pseudo-total content. Chloride, sodium and potassium concentrations in leachate exceeded the range recommended for soils, thus implying a risk of salinization of the soil. In order to remove soluble salts from fine fractions, a washing process is suggested. Soluble nitrate and phosphate concentrations were also above recommended values for regular soil, displaying strong variations within one particle size range. Ammonium concentrations were found to be within the recommended range, suggesting that nitrification had taken place in the landfill due to microbiological activity. The high concentrations of nutrients may lead to eutrophication of the ground and surface waters in the vicinity of the potential application area. Thus, concentrations of these constituents should be decreased in the fine fractions <4.5 mm, e.g. by a washing process. Sulphate concentrations were above limit values for 10:1 leachates, although these cannot be directly applied.

Pseudo-total contents for nickel were below limit values, although with soluble concentrations above the recommended values for soils and in the range of the limit value for recycling of excavated soils. These values were in agreement with previous data (Burlakovs et al., 2016), implying that further treatment technologies should focus on immobilisation rather than on removal of Ni. For example, Rabelo Monich et al (2018) describe waste-derived glass ceramics obtained from plasma gasification of MSW with leachable concentrations of only 0.003 to 0.009 mg/kg DM, i.e. two

TABLE 5: Soluble concentrations (liquid: solid ratio (L/S) 5:1, data refer to dry matter (DM)) of investigated fine fractions (n=3, s=1σ), bold parameters are above threshold values, limit values for excavated soil landfills (L/S 10:1) according to Federal Ministry for Agriculture, Forestry, Environment and Water Management (2008), for recycling quality class BA (L/S 10:1) according to Federal Ministry for Sustainability and Tourism (2017), recommended values for normal soil according to Austrian Standards (2013).

Parameter	Unit	4.5-1.6 mm	1.6-0.5 mm	0.5-0.18 mm	<0.18 mm	Limit value for excavated soil landfills	Limit value for recycling (class BA)	Recommended values for normal soil
pH	-	7.65±0.08	7.66±0.04	7.81±0.04	7.81±0.04	6.5-11	4.5-9.5	5.5- 8.8
Electric conductivity	[mS/m]	192±28	226±38	167±22	290±14	150	150	-
NH_4^+	[mg/kg DM]	83±61	61±4	32±4	70±8	10	10	7.5-75
F^-	[mg/kg DM]	3.41±0.90	3.43±1.11	2.61±0.55	3.22±0.90	20	20	
Cl^-	[mg/kg DM]	261±74	310±95	166±46	327±84	-	-	7.5-75
NO_3^-	[mg/kg DM]	287±379	328±450	165±208	332±440	443	443	37.5-150
PO_4^{3-}	[mg/kg DM]	10±6	9±3	5±2	12±3	15	15	0.1-2.25
SO_4^{2-}	[mg/kg DM]	4297±833	5700±1366	4501±1132	8834±190		2500	
TOC	[mg/kg DM]	344±18	416±28	257±26	471±20	200	100	15-338
B	[mg/kg DM]	1.75±0.25	2.00±0.28	1.20±0.18	1.90±0.19	-	-	0.226-0.525
Na	[mg/kg DM]	224±33	259±43	139±20	260±42	-		3-30
Mg	[mg/kg DM]	127±28	163±41	96±27	186±31	-		7.5-45
Al	[mg/kg DM]	0.33±0.08	0.42±0.06	0.55±0.16	0.45±0.06	-	-	0.075-0.750
Si	[mg/kg DM]	6.45±0.24	6.22±0.20	3.35±0.30	5.64±0.32	-		0.053-2.07
K	[mg/kg DM]	251±29	281±31	171±18	306±33	-		15-75
Ca	[mg/kg DM]	1727±265	2239±435	1649±383	3331±203	-		7.5-75
V	[mg/kg DM]	<0.005	<0.005	<0.005	<0.005	-		<0.045
Cr	[mg/kg DM]	0.01±0.00	0.02±0.00	0.01±0.00	0.02±0.00	1	0.5	<0.023
Mn	[mg/kg DM]	0.93±0.46	1.23±0.65	0.75±0.44	1.42±0.55			0.015-15
Fe	[mg/kg DM]	0.34±0.01	0.35±0.03	0.26±0.02	0.39±0.04			0.30-13.5
Co	[mg/kg DM]	0.03±0.01	0.04±0.01	0.02±0.01	0.05±0.01	1	1	0.002-0.075
Ni	[mg/kg DM]	0.34±0.18	0.39±0.19	0.23±0.09	0.42±0.19	-	0.4	<0.023
Cu	[mg/kg DM]	0.45±0.42	0.47±0.44	0.26±0.08	0.51±0.48		2	0.023-0.90
Zn	[mg/kg DM]	0.30±0.08	0.39±0.09	0.23±0.06	0.44±0.07	20	4	0.03-0.75
As	[mg/kg DM]	<0.05	0.06±0.00	<0.05	0.06±0.01	0.5	0.5	<0.011
Se	[mg/kg DM]	<0.05	<0.05	<0.05	<0.05	-	0.1	0.008-0.038
Mo	[mg/kg DM]	0.10±0.03	0.15±0.03	0.10±0.03	0.20±0.02	-	0.5	0.023-0.375
Cd	[mg/kg DM]	<0.005	0.005±0.00	<0.005	0.006±0.001	0.05	0.05	<0.005
Sn	[mg/kg DM]	0.01±0.00	0.01±0.00	0.01±0.00	0.01±0.00	2	2	<0.008
Ba	[mg/kg DM]	0.35±0.03	0.36±0.03	0.33±0.03	0.41±0.02	10	10	
Hg	[mg/kg DM]	<0.005	<0.005	<0.005	<0.005	0.01	0.01	<0.002
Tl	[mg/kg DM]	<0.005	<0.005	<0.005	<0.005			<0.002
Pb	[mg/kg DM]	0.01±0.00	0.01±0.00	<0.005	0.01±0.00	1	0.5	<0.075

orders of magnitude below the values obtained for fine fractions in this study. On the contrary, Cu, Pb, and Zn, which far exceeded limit values for pseudo-total contents, were characterised by very low leaching in the range of recommended values for soils, thus indicating how use of a removal technology to decrease total content may be more appropriate.

To summarize, with regard to leaching behaviour, the release of soluble salts from the investigated materials is more problematic than release of heavy metals. The low leaching of heavy metals from ELFM fine fractions confirms previous data (Burlakovs et al., 2016).

3.4 Mineralogical Analyses

XRD analyses of each two samples of the finest particle size ranges (0.5 to 0.18 mm and <0.18 mm) indicate a composition of approx. 70 to 80 wt.% quartz (α-SiO_2), 10 wt.% calcite ($CaCO_3$), 10% feldspars and minor amounts of kaolinite ($Al_4[(OH)_8|Si_4O_{10}]$), illite ($(K,H_3O)Al_2(Si_3Al)O_{10}((H_2O,OH)_2)$, siderite ($FeCO_3$) and gypsum ($CaSO_4 \cdot 2H_2O$) with no significant differences between the two particle size ranges (Figure 7, Table 6). The two samples from the fraction 0.5 to 0.18 mm displayed more consistent differences between each other than to the finest particle size

TABLE 6: Mineralogical composition of the particle size ranges 0.18 to 0.5 mm and <0.18 mm from batches 1 and 2 (n.d.: not detected).

Phase	Unit	B1_0.18-0.5 mm	B1_<0.18 mm	B2_0.18-0.5 mm	B2_<0.18 mm
Quartz, SiO_2	wt.%	80	73	80	72
Calcite, $CaCO_3$	wt.%	6	10	10	13
Microcline, $KAlSi_3O_8$	wt.%	12	4		n.d.
Plagioclase, $NaxCa_{1-x}Al_{2-x}Si_{2+x}O_8$	wt.%	n.d.	4	n.d.	3
Siderite, $FeCO_3$	wt.%	1	1	2	2
Kaolinite, $Al_4[(OH)_8\|Si_4O_{10}]$	wt.%	1	1	n.d.	1
Gypsum, $CaSO_4$•2H2O	wt.%	1	2	n.d.	3
Illite, $(K,H_3O)Al_2(Si_3Al)O_{10}((H_2O,OH)_2$	wt.%	n.d.	1	8	6

range <0.18 mm. Thus, the hypothesis that the fraction 0.5 to 0.18 mm may be enriched in silicates could not be confirmed mineralogically.

Microprobe EDX analyses of sample B1_<0.18 mm (Figure 8) suggest that Pb is present in metallic form or as (hydr)oxide. Elemental distribution maps taken by WDX from the same area do not indicate oxygen in the respective area, indicating the presence of Pb in metallic form (Figure 9), also in agreement with the low leachability of Pb from the investigated sample. With respect to the potential utilization of the investigated sample as soil substitute, the risk of a release of significant amounts of Pb into ground water is very low, although a direct route from soil to (human) mouth cannot be excluded. It is indeed for this reason that technologies capable of removing Pb-containing particles should be considered. The elemental map of Pb (Figure 9), in combination with the backscattered electron image (Figure 8), suggest that the dimensions of individual metallic lead grains are only a few µm, although forming an agglomerate of approx. 100 µm in size. These agglomerates might be separated from the other particles due to their different density (Pb: 11.34 gcm^{-3}; quartz: 2.65 gcm^{-3}), e.g. by jigging or heavy-media separation.

Zinc is associated with S according to EDX analyses. WDX analyses revealed a complete absence of oxygen in the respective area, i.e. Zn is present as ZnS, either as sphalerite (α-ZnS) or wurtzite (ß-ZnS). The observed low leaching of Zn (Table 5) indicates a high stability of these phases under the experimental conditions. However, it should be taken into account that ZnS might be oxidized by atmospheric oxygen and water, which yields dissolved Zn and sulphuric acid, thus potentially posing a long-term risk when using the investigated sample as soil substitute. Removal of ZnS grains is highly challenging due to their grain size of few µm and, compared to Pb, a less pronounced tendency to form agglomerates (Figure 8). Existing technologies to separate ZnS in this grain size, e.g. froth flotation (Peleka, Gallios, & Matis, 2017), are too expensive for use in the production of a soil substitute. Hence, maintaining reducing conditions through addition of biochar may represent an interesting option for use in ensuring low levels of Zn leaching (Houben, Evrard, & Sonnet, 2013).

Ba is associated with S according to EDX and also with O according to WDX, i.e. present as $BaSO_4$, barite, which is characterized by a very low solubility (about 1.4 mg/L

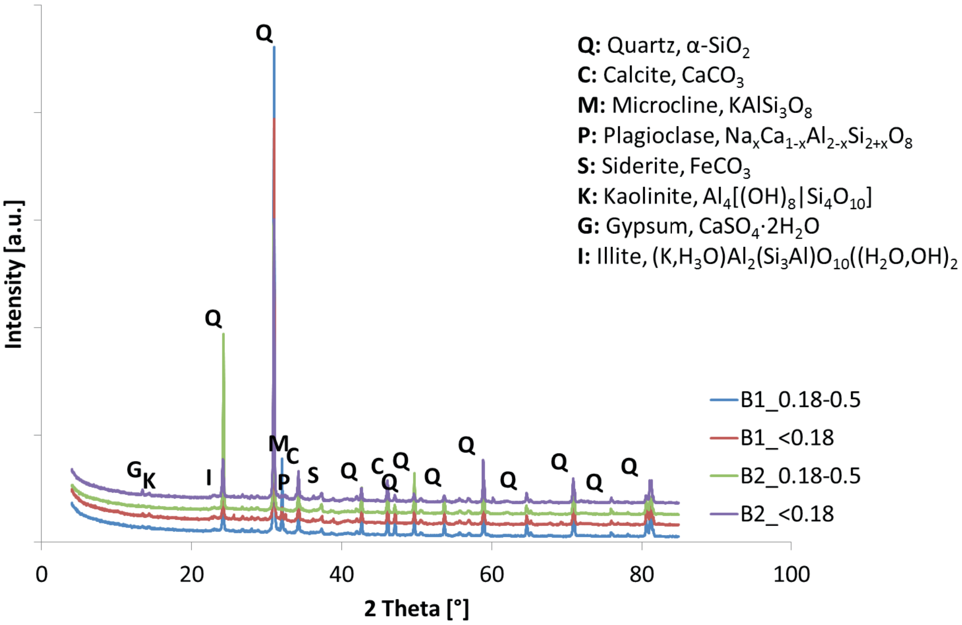

FIGURE 7: XRD patterns of the fine fractions 0.18 to 0.5 mm and <0.18 mm from batches 1 and 2.

at 25°C (Blount, 1977)). This is in agreement with the observed low leaching of Ba (Table 5). In contrast to Zn, which may be mobilized due to oxidation of sulphide, the same is not observed with Ba, which occurs already as sulphate. Barite itself is not hazardous, thus the presence of Ba as barite does not pose an environmental risk when using the investigated sample as soil substitute.

Cu is diffusely distributed, which suggests its presence as an adsorbed species (Figure 9). The very low leaching of Cu from the investigated sample (Table 5) is in agreement with the slightly alkaline pH of the leachate which favours adsorption of cations, e.g. Cu^{2+}, on the surfaces of minerals and organic matter. However, to avoid oral ingestion, e.g. by children, and ensure compliance with the threshold value for pseudo-total content of Cu, this element should be removed from the material prior to utilization as soil substitute. To desorb Cu from the surfaces, they will need to be charged positively, which can be done by acid washing and may prove to be an interesting option to condition the material for use as soil substitute.

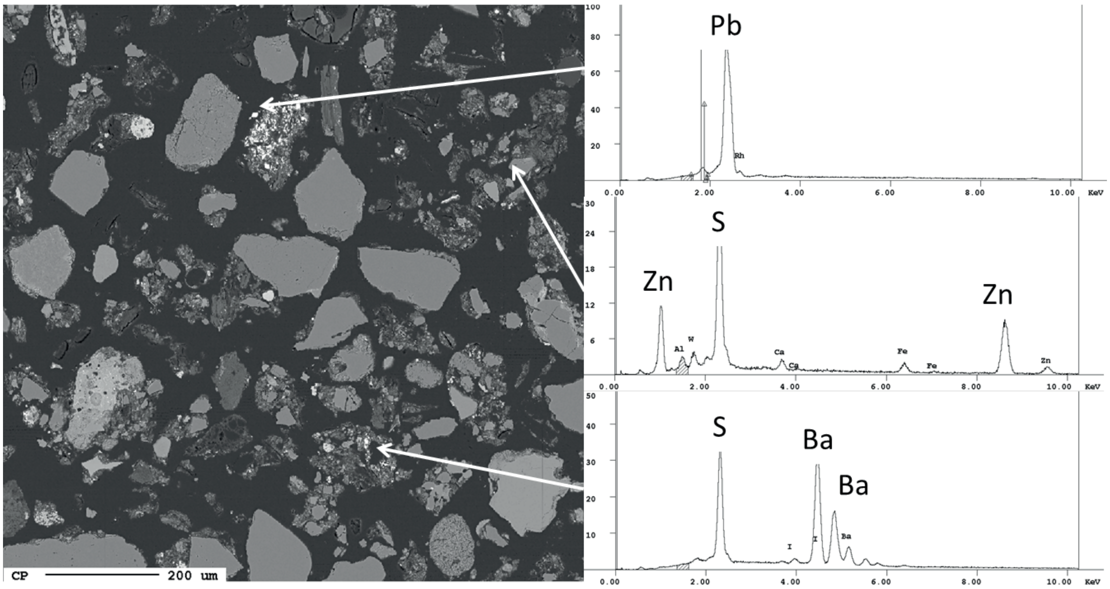

FIGURE 8: Backscattered electron image (left) and EDX spot analyses of heavy metal bearing phases in sample B1_<0.18 mm.

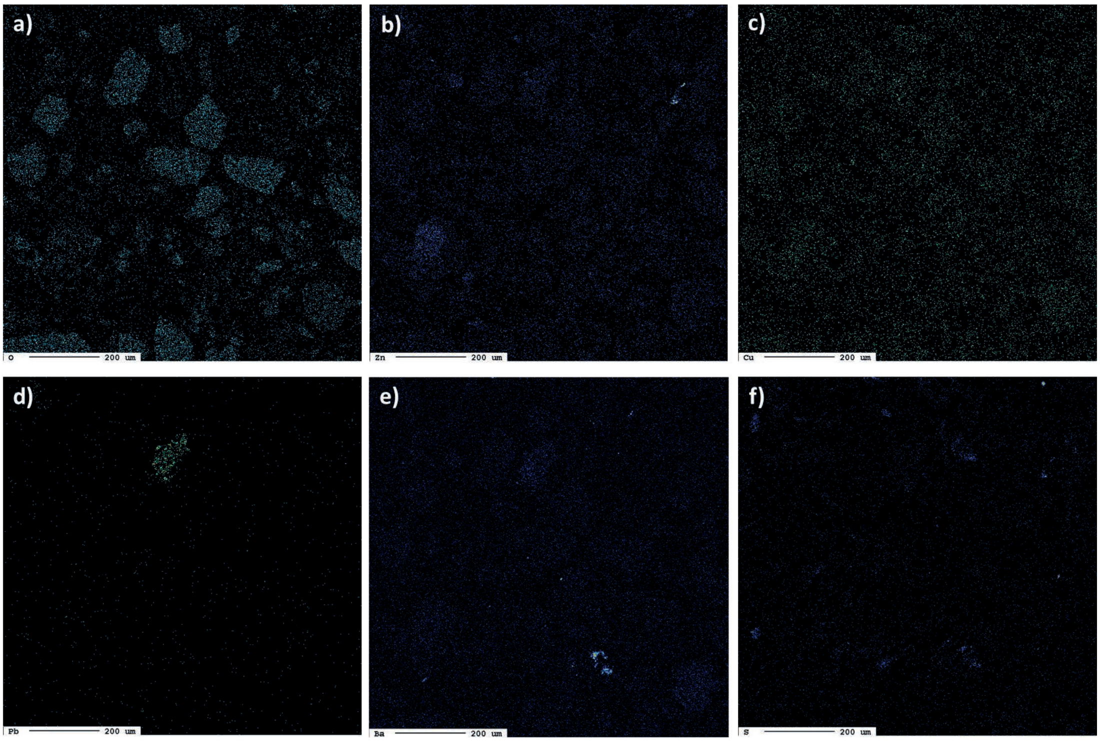

FIGURE 9: Elemental mapping of (a) oxygen, (b) Zn, (c) Cu, (d) Pb, (e) Ba, and (f) S in sample B1_<0.18 mm.

In sample B1_0.18-0.5 mm, Zn is associated with Fe, but not with S according to EDX analyses (Figure 10). WDX mappings indicate that no O is present in this grain, i.e. Zn is present as Fe-Zn alloy. However, it should be noted how only one Zn-containing grain was found in both B1_<0.18 mm and B1_0.18-0.5 mm, thus preventing any firm assumptions from being made with regard to Zn-containing phases in the particle size ranges. However, Zn leaching of this sample is similarly low in all fractions and both Fe-Zn alloys and ZnS are characterized by a low solubility. In both samples, Zn-containing grains are in the range of a few µm. With respect to separation of Zn, presence of the latter in Fe-Zn alloys would enhance the use of additional technologies such as jigging or heavy-media separation, which cannot be used for ZnS.

EDX spectra of individual particles (Figure 10) and WDX elemental distribution maps (Figure 11) confirm the presence of Ba as barite and the diffuse distribution of Cu.

In contrast to sample B1_<0.18 mm no Pb could be detected in sample B1_0.18-0.5 mm.

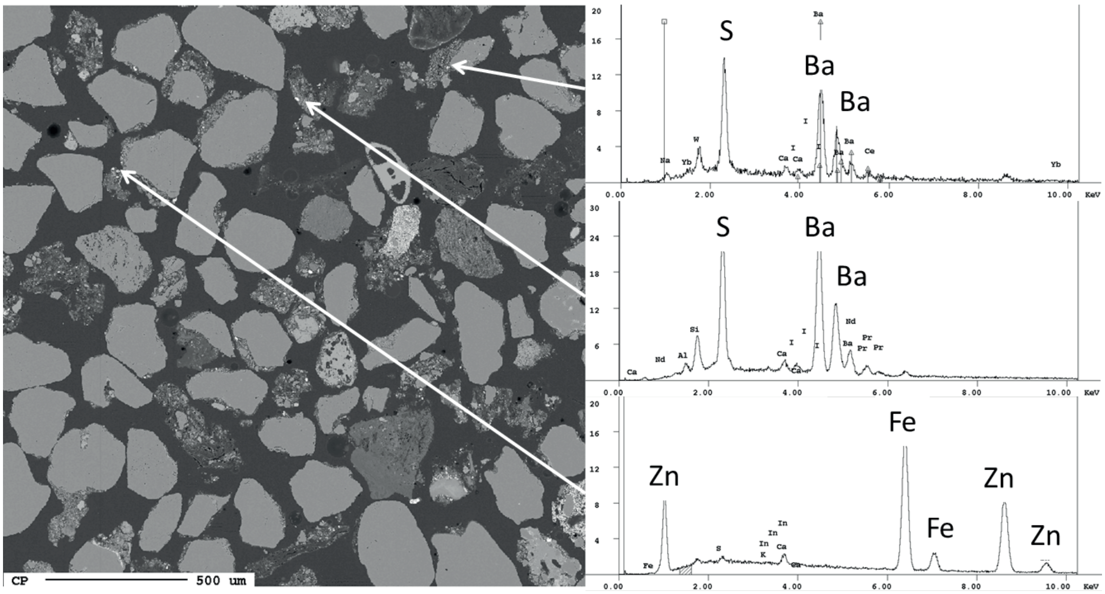

FIGURE 10: Backscattered electron image (left) and EDX spot analyses of heavy metal bearing phases in sample B1_0.18-0.5 mm.

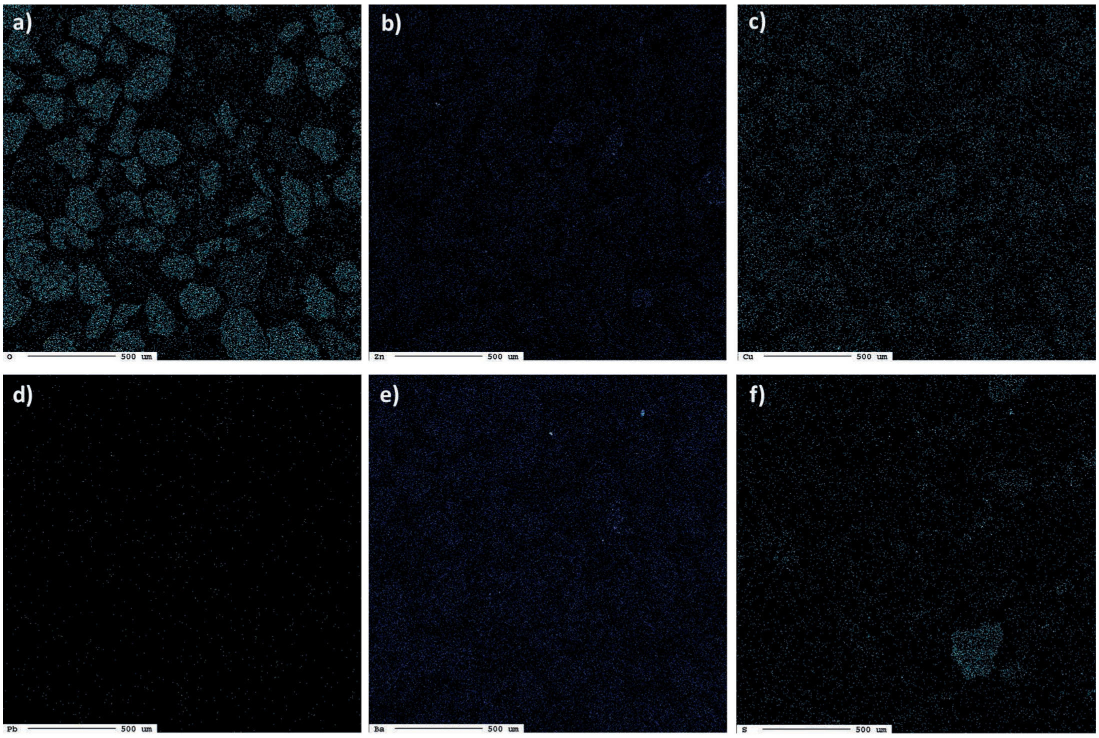

FIGURE 11: Elemental mapping of (a) oxygen, (b) Zn, (c) Cu, (d) Pb, (e) Ba, and (f) S in sample B1_0.18-0.5 mm.

In sample B2-8_<0.18 mm, EDX analyses (Figure 12) indicated the presence of monazite, $(La,Ce,Nd)[PO_4]$, the most important ore mineral for rare earth elements (REE). Cerium, Nd and La have been reported in MSW landfills in the range of 14-25 mg/kg, 8-12 mg/kg and 7-11 mg/kg, respectively (Gutiérrez-Gutiérrez et al., 2015), which is below the average concentrations in the continental crust (Taylor, 1964) and of no economic or ecological relevance. However, the mineralogical bonding of REE in MSW landfills has not to date been investigated. EDX analyses clearly indicate that Thorium (Th) is incorporated in the investigated monazite grain, thus causing environmental concern due to its radioactivity. Considering that this grain with a size of few µm is the only one in the entire investigated sample, the environmental impact is negligible.

As in sample B1-8_<0.18 mm, EDX analysis shows the association of Zn with S (Figure 12) and WDX elemental mapping (Figure 13) indicates the absence of O in this grain, meaning that Zn is present as zinc sulphate. As hydrogen cannot be measured, it remains unclear if the wa-

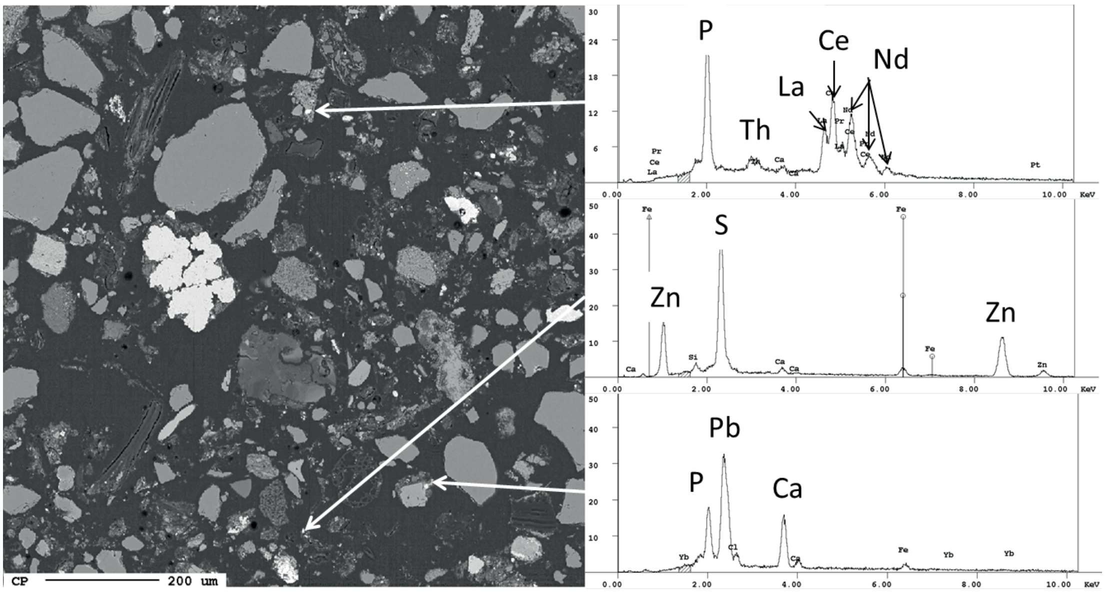

FIGURE 12: Backscattered electron image (left) and EDX spot analyses of heavy metal bearing phases in sample B2_<0.18 mm.

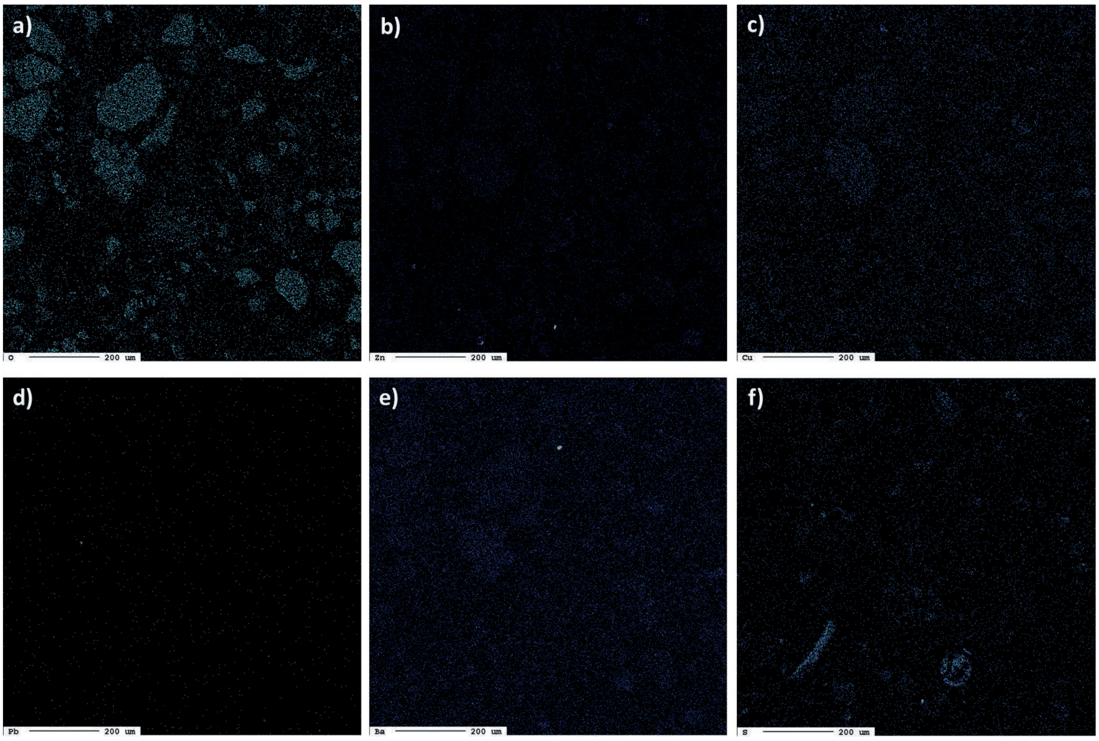

FIGURE 13: Elemental mapping of (a) oxygen, (b) Zn, (c) Cu, (d) Pb, (e) Ba and (f) S in sample B2_<0.18 mm.

ter-free zincosite ($ZnSO_4$) or the water-containing phases gunningite ($ZnSO_4 \cdot H_2O_2$), boyleite ($ZnSO_4 \cdot 4H_2O_2$), goslarite or zinc melanterite (both $ZnSO_4 \cdot 7H_2O_2$) are present. It is suggested that more oxidizing conditions were present in this sample compared to the other two samples, where Zn was present as ZnS. However, as leaching does not significantly differ between the samples, the difference in mineralogy does not seem to produce a significant impact on environmental performance. EDX pattern indicates the presence of a calcium lead phosphate (Figure 12), although WDX mappings suggest the absence of Pb. As in the other samples, WDX mappings indicate the diffuse distribution of Cu within the sample.

In sample B2_0.18-0.5 mm, EDX analyses confirmed the association of Zn and S (Figure 14). In contrast to the other samples, this phase is not present as individual grain, but forms a rim around a quartz grain. WDX mapping of O (Figure 15) also reveals the presence of oxygen in this rim, i.e. Zn is present as $ZnSO_4$, as in sample B2-8_<0.18 mm. EDX patterns also confirmed the presence of Ba as barite,

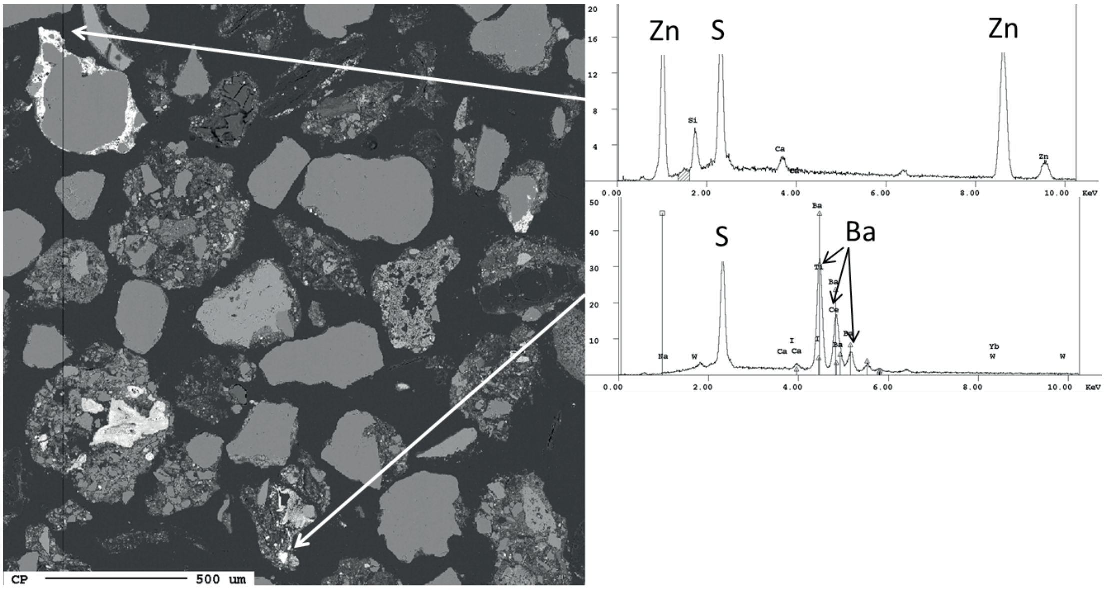

FIGURE 14: Backscattered electron image (left) and EDX spot analyses of heavy metal bearing phases in sample B2_0.18-0.5 mm.

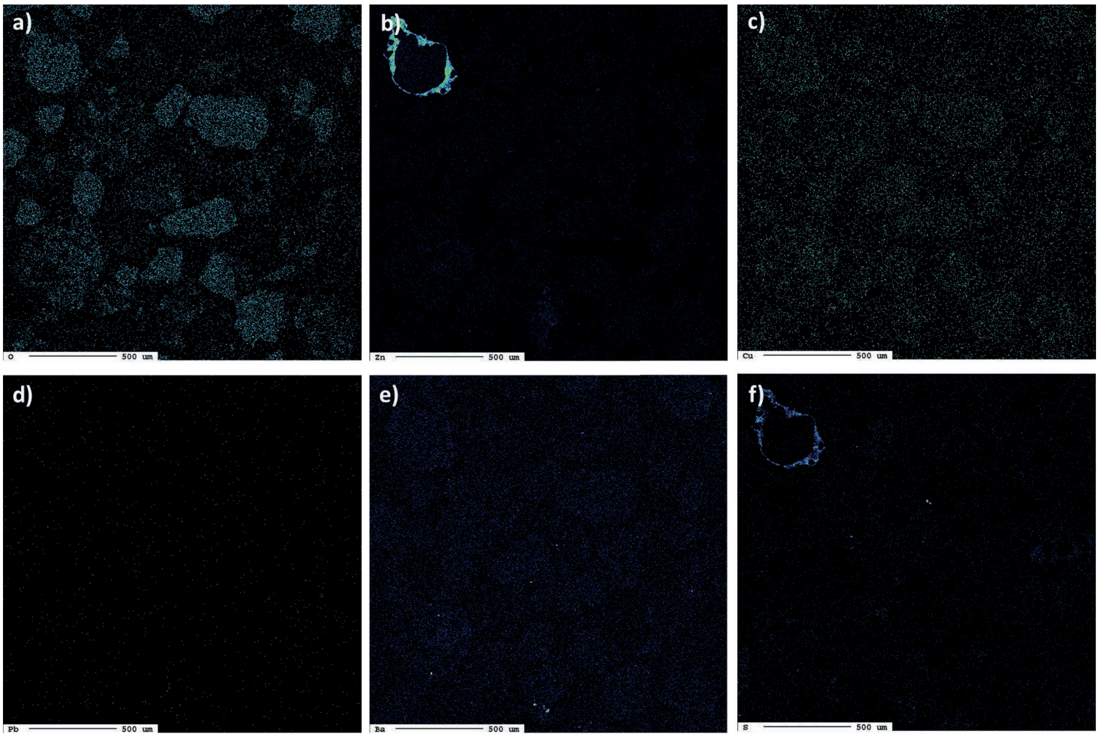

FIGURE 15: Elemental mapping of (a) oxygen, (b) Zn, (c) Cu, (d) Pb, (e) Ba and (f) S in sample B2_0.18-0.5 mm.

BaSO$_4$. Pb could not be detected in this sample, whereas Cu is randomly distributed in the same way as in other samples (Figure 15).

To summarize, mineralogical investigations confirm the presence of Pb as metal and as Pb-Ca phosphate, Zn as Fe-Zn alloy, sulphide and sulphate, Ba as barite, Cu adsorbed to mineral surfaces and REE as monazite. This stable incorporation (and in case of Cu, adsorption) explains the low leaching of heavy metals from the investigated samples. However, the mineralogical bonding of Ni, characterised by rather high leaching, is in agreement with observations from natural rocks (Vollprecht et al., 2019).

4. CONCLUSIONS

Fine fractions are a major obstacle for the economic feasibility of (E)LFM. Although screening and density separation may be used to recover significant amounts of combustible and inert materials, the fine-grained soil-like materials remain an important challenge.

In this study, we refute our first working hypothesis according to which screening in the range <4.5 mm allows for a separation into a clean coarser fraction and a contaminated finer fraction. Conversely, we confirmed our second working hypothesis, i.e. that the mineralogy of ELFM fine fractions is related to their leachability, as several host phases for low-leaching elements such as a Fe-Zn alloy, ZnS and ZnSO$_4$, metallic Pb and Pb-Ca phosphate, were identified.

Briefly, the main problematic factors in the recycling of ELFM fine fractions are represented by the high pseudo-total contents of organic carbon and heavy metals, in the present case study Cu, Zn, Cd, Hg and Pb, which hinder use of these fractions in countries in which limit values for pseudo-total contents have been established in environmental legislation. In countries regulating only the leachable contents of heavy metals, the utilization of fine fractions from (E)LFM seems more realistic, as this study shows that the majority of heavy metals is tightly bound in low-soluble mineral phases or strongly adsorbed to mineral surfaces.

A remaining challenge in the present case study is the rather high leaching of Ni, which may be encountered when using immobilization technologies. Further research is needed to investigate both the adverse effects of carbon speciation, such as methane formation, and beneficial effects including carbon sequestration in stable humic substances.

In a broader scope, future research on fine fractions from ELFM should be conducted to investigate alternative uses, e.g. as landfill liner (Liebetegger 2015) or other consituent in an “aftercare-free landfill”. For this purpose, a low hydraulic conductivity and low leaching of heavy metals might be sufficient, particularly as the material would continue to be considered a waste, with no need to meet end-of-waste criteria need. Therefore, an intelligent use of the fine fractions to minimize aftercare needs seems to represent the most promising option. A saving on aftercare costs and consideration of the real estate/ecosystem services (Burlakovs et al., 2017) may provide new pathways for future ELFM projects and should be investigated.

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12 SUMMARY

As introduced in the Section 1.2 “Framework of Doctoral Thesis” of the Introduction, this chapter comprises a synthesis of the principal findings of each scientific article, as well as of the answer to the formulated research question. This information is presented below per scientific article and follows the same order in which the scientific articles have been enclosed and discussed throughout this cumulative doctoral thesis.

12.1 Scientific Article No. 1

Legacy landfills and dumpsites represent a source of health and environmental hazards, as well as significant long term maintenance and aftercare expenses. Additionally, the growing need to switch from an unsustainable currently linear economy to a circular one, in which residual materials can become input materials in their production chains or in alternative ones, is pushing our common practices to adopt a more sustainable approach in our production processes and usage habits. This change of mindset includes viewing legacy landfill sites and dumpsites as alternative sources of energy and materials, instead of as “perpetual” waste and carbon sinks. The latter approach is commonly known as LFM, which targets to recover energy and materials from waste disposed of in old landfills, while addressing pollution mitigation and land remediation and reclamation, among others.

Over the last decade, LFM has evolved into a holistic concept called ELFM, in which the main drivers of LFM are pursued in compliance with the most stringent social and environmental criteria and, in addition, innovative exploration and transformation technologies are employed for an integrated WtM and WtE valorization. Different strategies can be implemented in order to integrate (E)LFM into current waste management systems, which address (E)LFM to different extents and are associated to their own specific conditions. To this end, a multi-criteria approach is needed to assess the environmental, economic and societal aspects of each strategy. This multi-criteria assessment approach is directly influenced by technologic and site-specific factors as well, such as available technologies, waste characteristics, market conditions and applicable regulations.

The implementation of (E)LFM is discussed in this scientific article in four scenarios: “do-nothing” or “business as usual”, classic remediation with re-landfill, classic LFM with RDF state-of-the-art (co-)incineration and ELFM. The latter scenario corresponds to the most advanced and lean strategy, and it is also the approach proposed by the NEW-MINE project, in which a plasma gasification process is applied for the exploitation of the material and energy recovery potential of landfill-mined waste and the immobilization of pollutants.

Research question: What are the main challenges for (E)LFM and how to integrate it into current waste management?

The main challenges to be overcome by (E)LFM are the following:

- The potential for material and energy recovery and land reclamation is case specific

- High operational costs and low market prices for primary and secondary raw materials. In the case of ELFM high capital expenditures as well
- Subject to legal uncertainty and/or deficiency, as well as to additional taxes and fees
- Lack of specific procedures, guidelines and standards
- Public opposition
- Current lack of a common and integrated framework for a holistic multi-criteria assessment of (E)LFM, in which also societal aspects are addressed

Similarly to the potential of a certain landfill site for the feasible implementation of (E)LFM, the integration of (E)LFM into current waste management systems is case specific and mainly depends on technical, economic, environmental and societal aspects. Therefore, studies on the characteristics of the landfill site and neighboring areas, the waste contained in the landfill, potential of marketability of secondary materials, the applicable environmental regulations and the position of the inhabitants of the region before (E)LFM activities belong to the preliminary and essential activities to be carried out. For this purpose, geophysical methods could be employed to gather information about the landfill site and waste composition in a rough manner without the need of invasive methods, which could reduce costs in a significant way. Moreover, the separation of the landfill-mined waste into potentially recoverable materials can be achieved by implementing a relatively simple mechanical processing approach, which is to be conceived according to the particular characteristics of the landfill´s waste and available technology. Furthermore, adequate WtM and WtE valorization strategies are to be identified in agreement with the applicable environmental regulations and market conditions, as well as with the technological and economic development of the place in question.

On the side of the more advanced waste processing methods, plasma gasification could enable the recovery of energy through the production of high quality energy carriers, such as hydrogen or methane, from the high calorific fractions and the upcycling of its residues into high value-added eco-friendly construction materials based on inorganic polymers and glass-ceramics. In less complex management systems, the produced calorific fractions could be used in (co-)incineration for the recovery of energy in the form of electricity and heat. As for the produced inert materials and fine fractions, it is of crucial importance to include them into the scope of the valorization schemes, since these fractions represent most of the landfilled-mined waste, which could be done by e.g. producing substitutes for construction aggregates and soil in construction applications. Although ferrous and non-ferrous metals typically represent a small share of landfill-mined waste, these materials belong to the recovered materials through (E)LFM with the highest market value and, thus, they can account for significant revenues. To this end, the recycling industry of ferrous and non-ferrous metals is normally well developed and is considered able to incorporate metals from ELFM in its processes in most cases.

Therefore, the previous aspects are to be tailored case by case in such a way that the technical, economic and environmental feasibility of the project can be achieved, while the applicable regulations are observed as well.

12.2 Scientific Article No. 2

Typically, the fine fractions account for 40-80 wt.% of the total landfill-mined waste in (E)LFM projects, depending on the particle size selected as upper-size limit for their definition, as there is no existing convention in this regard to this day. Besides the particle size limit, the amount of the fine fractions can be influenced by the employed extraction and processing techniques in (E)LFM projects; into this respect the age and type of waste of the landfill can also play a relevant role.

The water content in the fine fractions has shown strong variations among investigations (14-79 wt.%) and elevated contents have been associated with processability difficulties in dry processing methods. Regarding the bulk density, previous studies have also reported values with significant variations, which were in the range of 370-1250 kg/m^3. In turn, the particle size of the fine fractions has presented a tendency to decease over time and to increase with depth within the landfill body, which suggests that older landfills can yield higher amounts of fine fractions and that their amount will also increase as the excavation activities approach to the bottom of the landfill basin. These parameters are closely interrelated and are of decisive relevance for the selection of adequate mechanical processing methods and the identification of appropriate WtE and WtM valorization routes. Moreover, the fine fractions are mainly composed of degraded organic waste and weathered inert materials, such as cover layer material (e.g. clay) and concrete, bricks, glass and stones, respectively, followed by smaller amounts of materials with high calorific values, e.g. plastics, textiles, wood, paper and cardboard, and minor quantities of ferrous and non-ferrous metals.

The previous information reveals that the fine fractions could be a relevant source for material and energy recovery and, hence, their further investigation is necessary within the framework of (E)LFM.

Research question: What are the main characteristics of the fine fractions and why are they of utmost importance in (E)LFM?

The main characteristics of the fine fractions are:

- Share with respect to the total amount of landfill-mined waste
- Water content
- Bulk density
- Particle size distribution
- Material composition
- Correlations among the above mentioned characteristics

These fractions are of critical relevance in (E)LFM because they frequently account for the largest share of the landfill-mined waste, which has been largely discarded in previous LFM projects despite their theoretical potential for material and energy recovery. This situation has severely undermined the environmental and economic feasibility of previous projects, since most of the extracted material has been directed back into the landfill; generating significant additional operational costs, keeping maintenance and aftercare activities at the landfill site and hindering land reclamation: the latter being one of the main economic drivers in LFM. This has been the case as the fine fractions present difficult characteristics for further processing, such as elevated water content, small particle size and the presence of organic and inorganic pollutants.

Therefore, it is of utmost importance in (E)LFM to incorporate the fine fractions into the scope of the WtM and WtE valorization schemes, which could be done through the selection of adequate processing methods according to their main characteristics.

12.3 Scientific Article No. 3

As is the case for the potential of legacy landfills and dumpsites for (E)LFM, the potential of the fine fractions for material and energy recovery is site specific as well. The amount and type of pollutants present in the landfilled waste play a crucial role in the selection of the processing methods and valorization schemes, which directly influence the viability of the implementation of (E)LFM in a certain landfill. Stabilized landfills or dumpsites without biogas and leachate collection infrastructure could be appealing candidates for (E)LFM, as they lack the investment in such infrastructure and could pose lower risks for LFM activities. The location of the site, configuration, infrastructure, operation procedures and historical records, as well as the main characteristics of the waste and of the fine fractions, correspond to the essential initial information of the site to be evaluated in (E)LFM projects. Environmental and health risks need to be assessed in every (E)LFM project as well.

A sound understanding of the processability of the fine fractions is of key importance for the selection of an adequate treatment and for the identification of appropriate valorization schemes. Given that recovered plastics, textiles, wood, paper and cardboard from the fine fractions normally present a poor quality, WtE results to be a better valorization alternative to WtM. The further development of processing technologies and the market, regulatory and societal aspects are among the main challenges to be overcome by (E)LFM.

Research question: How could the fine fractions be addressed in (E)LFM and what is the potential of these fractions for material and energy recovery?

The fine fractions are composed of different types of materials, which can be separated by means of their physical properties in a mechanical process. This mechanical processing is to be designed in such a way that the fine fractions can be sorted into different groups of materials that have certain properties in common (e.g. form, particle size, density and composition) using the least amount of processing steps in an effective and efficient manner. In addition, the problematic elements and compounds (i.e. pollutants) could be concentrated in a certain fraction (i.e. residual material) through mechanical processing.

According to the typical characteristics of the fine fractions identified in the scientific article no. 2, these fractions could be sorted into 5 groups of materials: combustible, inert and soil-like materials, metals (ferrous and non-ferrous) and a residual material. The combustible materials could be used to produce an alternative fuel (e.g. RDF/SRF) that can be valorized through thermo-chemical conversion processes, such as (co-)incineration, pyrolysis and gasification;

while the inert materials could be utilized to substitute construction aggregates (e.g. sand and gravel). The soil-like material, which is mainly composed of cover layer material, soil, degraded organic waste and weathered inert materials, could be employed, to a certain extent, to produce a substitute for soil in construction applications, cover material for operational landfills, soil for non-edible crops or formation of bio-soils for environmental remediation activities: provided that this material complies with the applicable regulations. The recovered ferrous and non-ferrous metals could be directly sent to the metal recycling industry, and the residual fraction would need to be stored until further treatment technologies are developed or its treatment becomes economically feasible.

In this way, most of the fine fractions could be valorized in WtM and WtE schemes, which would largely contribute to the environmental and economic feasibility of (E)LFM and thereby address these problematic fractions to a great extent.

12.4 Scientific Article No. 4

A case study was selected to study the full implementation of ELFM within the framework of the NEW-MINE project. This case study corresponds to the MSG landfill, which was one of the main disposal sites of MSW, C&D and IW of the Wallonia region in Belgium and from which a total of approx. 370 Mg of landfilled waste was excavated for this investigation. The selection of the excavation zone was done according to the results of geophysical explorations throughout the old part of the landfill, which successfully quantified the thickness of the cover layer at the excavation area and identified the presence of electroconductive and non-electroconductive materials, such as metals and inert waste, respectively.

The landfill-mined waste was 40-50 years old and was directly pre-processed with a ballistic separator after excavation. The ballistic separator processed an avg. of ca. 200 m^3/h, which separated the waste into 3D and 2D materials and an under-screen fraction. Two ballistic separation steps were performed simulating a cascade arrangement: the first with screen-paddles of 200 mm and the second one with 90 mm. The obtained fractions, 3D ≥200 mm, 2D ≥200 mm, 3D 200-90 mm and 2D 900-90 mm were considered as the coarse fractions in this case study, while the material <90 mm was classified as the fine fractions. Characteristics, such as water content and material composition, of the obtained fractions from the ballistic separation process were determined, as well as the calorific value and ash content of the 2D fractions. Additionally, the effectivity of the tested ballistic separator (Stadler STT 6000) and its suitability for landfill-mined waste were evaluated in this study.

Research question: What are the main characteristics of the excavated material from the Mont-Saint-Guibert landfill and how could this material be initially processed?

The landfill-mined waste presented an avg. water content of about 30 wt.% and an avg. bulk density of around 800 kg/m^3. The excavated waste was constituted of about 62 wt.% fines <20 mm, 21 wt.% inert, 4.7 wt.% plastics, 3.5 wt.% glass and 1.8 wt.% metals, as well as of smaller amounts of paper, wood, textiles and unidentified materials. About 15 wt.% of the total processed amount with the ballistic separator accounted for the 3D fractions, while around

8 wt.% corresponded to the 2D fractions. The remainder amount, ca. 77 wt.%, accounted for the fine fractions <90 mm.

The obtained 3D fractions were mainly composed of inert materials, such as C&D waste, with a slight amount of combustible materials, such as wood, hard plastics and metals, and impurities in the form of fine fractions, which after further processing could be used to replace construction aggregates and recover ferrous and non-ferrous metals. In turn, the 2D fractions mostly consisted of plastics foils and textiles, and a minor amount of metals and impurities as well. After metal recovery, the 2D fractions could be employed as RDF in thermo-chemical valorization processes. These fractions presented a gross calorific value of around 20 MJ/kg and an ash content of about 44 wt.%.

The results of the material characterization reveal that a significant additional amount of materials could be recovered from the fine fractions after further processing, which is the focus of the scientific article no. 5. In this study it was demonstrated that landfill-mined waste can be sorted into the targeted output fractions directly after excavation by means of a robust ballistic separator in an effective and efficient way and, therefore, ballistic separation proves to be a suitable and convenient pre-processing method for landfill-mined waste, which can precondition the processed material for further processing in a reduced number of processing steps, in order to enable material recovery from landfill-mined waste.

12.5 Scientific Article No. 5

The main physical characteristics of the fine fractions <90 mm from the MSG landfill were determined through studies on the water content, bulk density, particle size distribution and material composition, as well as on the interactions among them. This information is essential for the conceptual phase of the treatment process and valorization strategies.

A mass and water content distribution study according to particle size proved to be helpful to identify the particle size from which the fine fractions would need moisture adjustment (i.e. further wetting or drying) or be processed in wet or dry methods. That information could also be used to identify the maximum water content (i.e. optimal water content (owc)) with which the fine fractions could be processed in a dry mechanical process without the need of complete drying: reducing material losses in the form of dust and fine particles emissions, and reducing the energy demand of the drying process.

The methods employed and suggested in the present study have demonstrated to be a sound and successful approach of gathering the necessary information for the determination of the main characteristics of the fine fractions, as well as for the identification of potential valorization routes. Therefore, future investigations on fine fractions from ELFM are encouraged to follow the present approach, in order to improve the comparability among different case studies, as well as to facilitate the transferability of their results.

Research question: What are the main characteristics of the fine fractions of the Mont-Saint-Guibert landfill and what type of materials could be recovered from them?

The fine fractions <90 mm from the MSG landfill accounted for 77 wt.% of the pre-processed landfill-mined material with the ballistic separator. These fractions showed overall bulk density and water content in the ranges of 720-1000 kg/m^3 and 25-30 wt.%, respectively.

The studies on the water content, particle size distribution and material composition of the fine fractions revealed that the presence of water plays a key role in the occurrence of surface defilements and agglomerated materials, which can directly influence the performance of mechanical processing steps, such as particle size classification, metal extraction, density separation and sensor-based sorting, as well as on the quality of the output materials of the mechanical processing. The amount of surface defilements and agglomerates showed a tendency to increase with the increase of water content; however, this is only valid within a certain range of water contents and regarding dry processing methods, since the amount of surface defilements and agglomerates could be decreased to a great extent by processing the fine fractions in a saturated state in wet processing methods. Water content also influenced the bulk density of the fine fractions and its constituent materials: directly affecting mechanical processing steps in this way as well. For instance, the bulk density decreased by about 21 wt.% after drying. The material characterization of the fine fractions 90-10 mm presented median amounts of 32.4 wt.% inert, 8.0 wt.% combustibles and 1.3 wt.% metals (ferrous plus non-ferrous), while the fine fractions <10 mm account for 51.8 wt.% with respect to the total amount of fine fractions <90 mm.

Therefore, significant amounts of the fine fractions could be directed to WtM and WtE valorization schemes if these fractions are subjected to mechanical processing. Additionally, the amount of recovered materials could be significantly increased if these fractions are mechanically processed below 10 mm, since combustible and inert materials, as well as metals were still identified between 10 mm and 3 mm; moreover, the amount of the fine fractions to be stored for future treatment could also be decreased in this way.

The previous information is of decisive importance for the selection of adequate processing methods, as well as for the assessment of the WtM and WtE potential of the fine fractions from the MSG landfill.

12.6 Scientific Article No. 6

The findings of the research article no.5 together with those of this study led to the conclusion that, in order to optimally process the fine fractions from the MSG landfill, the approach to follow corresponds to a dry mechanical processing. This was the case because dry mechanical processing methods are considerably less complex and cost intensive than wet, chemical or mineralogical methods. Additionally, many dry mechanical processing methods have been successfully proven suitable for processing waste materials in an efficient and effective manner, as they can deal with the complex and heterogeneous nature of this type of material.

The processability of the fine fractions in the selected dry mechanical processing approach was evaluated in this investigation, as well as the effectivity and efficiency of the whole process, according to the outcomes of the scientific article no. 5. Additionally, the scope of the mechanical processing regarding the recovery of combustible and inert materials was extended down to a particle size of 4.5 mm, which might contribute to the overall economic and environmental feasibility of ELFM at the MSG landfill. Moreover, a study on the particle size distribution of the fine fractions with different water contents was performed in order to determine the owc, which corresponded to a water content of 15 wt.%. The selected mechanical processing approach was tested in both the owc and dry states, in order to determine the effects of the owc on the mechanical processing and quality of the recovered materials. The extent of the mechanical processing is directly associated to the quality of the outputs and the overall cost for processing the fine fractions.

Therefore, the mechanical processing of the fine fractions is to be conceptualized in such a way that the applicable quality requirements of the output fractions are met and the revenues of their valorization are not exceeded by the expenses for their production.

Research question: How could the fine fractions of the Mont-Saint-Guibert landfill be processed to enable material and energy recovery according to the previously identified potential?

The fine fractions <90 mm from the MSG landfill were processed in a dry mechanical process, which consisted of particle size classification, ferrous and non-ferrous metals extraction, density separation and sensor-based sorting steps. Through this approach the fine fractions were separated into combustibles, inert, ferrous and non-ferrous metals and soil-like materials, which follows the WtM and WtE strategies proposed in the scientific article no. 3. The particle size classification steps divided the fine fractions into the particle size ranges 90-30 mm, 30-10 mm and 10-4.5 mm and <4.5 mm, from which the particle size ranges 90-30 mm, 30-10 mm and 10-4.5 mm were further processed to recover combustibles, inert materials and metals.

The tested dry mechanical approach in the dry state produced total median amounts of 42.7 wt.% fine fractions <4.5 mm, 37.2 wt.% inert, 9.0 wt.% combustibles, 1.4 wt.% ferrous metals and 0.3 wt.% non-ferrous metals, and presented a median amount of 7.9 wt.% of material losses in the form of dust and fine particles emissions. The previous figures were in agreement with the expected quantities determined in dry state in the scientific article no. 5, taking into account that about 10 wt.% of additional material, distributed among all grouped material fractions, was recovered from the fine fractions by processing the fine fractions down to a particle size of 4.5 mm.

The obtained amounts between the owc and dry states showed slight differences, which were mainly attributed to the additional amounts of surface defilements and agglomerates present in the owc state than in the dry state, and the manner in which different materials interact with water (e.g. adsorb/absorb/repel). These discrepancies are not regarded as sufficiently high to conclude that the mechanical processing in the owc state was considerably less effective and efficient than the one in the dry state. Nevertheless, mechanical processing methods working by means of differences in size, mass, density and appearance, among others, can be affected in a significant way depending on the amount of surface defilements and agglomerates. Moreover, the impact of the additional amount of impurities present in the outputs of the mechanical processing in the owc state, concerning the quality of the outputs, is still to be studied through laboratory analysis.

Therefore, it was concluded that the dry mechanical processing tested in the present investigation proved to be a successful approach to separate the fine fractions into the intended fractions in an effective manner in both the owc and dry states.

12.7 Scientific Article No. 7

As part of the selected and tested dry mechanical processing approach of the fine fractions of the MSG landfill, high density combustible materials that could not be directed to the light fractions by means of the density separation steps, as well as those combustible materials that due to their particular shape or size were erroneously directed to the heavy fractions, were further processed with near-infrared (NIR) sensor-based sorting (SBS) in both the owc and dry states. This was done in order to remove the remainder of combustible materials from the heavy fractions and, thus, increase their purity and quality.

The amount of combustible materials still present in the heavy fractions showed a tendency to decrease as particle size decreased, which can be explained by the lower presence of recoverable materials, others than soil-like materials, identified in the scientific article no. 5, rather than by a better performance of the processing methods in smaller particle size ranges. In turn, the heavy fractions in the owc state showed a higher amount of combustible materials still present in them before the SBS steps, which can be attributed to the effects of the presence of water previously discussed in the research article no. 6. The decreasing enrichment ratios of the heavy fractions with particle size can be due to the also decreasing amount of combustible materials as the particle size reduces.

The extent of the previous mechanical processing of the input material, the water content, the amount of surface defilements and agglomerates, the material composition and the particle size (incl. the breadth of a particle size range) were identified as the most relevant factors influencing the performance of SBS in landfill-mined waste. Differentiating pulp-based materials from stony and rocky inert materials resulted problematic, especially in the presence of water. An acceptable steady performance of SBS steps in the fine fractions, as well as its effectivity and efficiency at industrial scale in (E)LFM, remains to be studied.

Research question: How could high density combustible materials be further removed from the heavy fractions of the fine fractions of the Mont-Saint-Guibert landfill and what are the main challenges of this method?

The remaining combustible materials in the heavy fractions produced by the density separation steps of the tested dry mechanical processing were removed with SBS by means of NIR in both the owc and dry states.

The recognition and separation of combustible from inter materials was successfully performed: raising the purity of the particle size ranges 90-30 mm, 30-10 mm and 10-4.5 mm of the heavy fractions from 85.6 wt.%, 93.7 wt.% and 98.8 wt.% to 99.6 wt.%, 97.7 wt.% and 99.4 wt.% in the owc state, and from 88.2 wt.%, 97.1 wt.% and 98.1 wt.% to 99.3 wt.%, 99.7 wt.% and 98.8 wt.% in the dry state, respectively.

Therefore, it was demonstrated that the amount of the combustible materials still present in the heavy fractions of the fine fractions can be reduced by means of NIR sorting.

The main challenges faced by NIR sorting in relation to the fine fractions of landfill-mined waste identified in this study were the following:

- Considerable amount of surface defilements and agglomerates
- Dust emissions in the dry state
- Small-sized particles are difficult to detect and sort out
- Black or dark materials cannot be differentiated by means of NIR
- Variable degradation state of certain plastics hinders steady accurate detection
- Vey light materials and materials that show a tendency to float or plane due to their shape or size cannot be adequately sorted out by means of air pulses from a nozzle
- Impact of sensor-based equipment on the overall economics of a (E)LFM project is a significant concern

However, the recognition of black or dark materials could be addressed by the utilization of color recognition (VIS), while by extending the employed algorithm to recognize materials in different degradation states the recognition of degraded plastics could be enhanced.

12.8 Scientific Article No. 8

The non-ferrous metals recovered from the fine fractions of the MSG landfill by means of the eddy-current separation steps in the tested dry mechanical processing were manually further sorted into non-magnetic Fe scrap, Cu scrap, Al scrap, heavy scrap and unknown metals. Subsequently, a portable XRF analyzer was utilized to subclassify these metals into Al-foils, Al packaging, Al-alloy, Brass, Cu-wires, Pb-alloy, stainless-steel, Zn-alloy and other metals, such as bronze, steel-tin cans, Ni and Ag scraps. These subclassified metals were subjected to 3 different approaches to assess their metal concentration and amount of surface defilements, which corresponded to ultrasonic cleaning, smelting and thermal treatment based on the de-coating process employed by the Al industry.

In general, a concentration of 4.8 kg of non-ferrous metals per Mg of landfill-mined waste was determined through the characterization of the material of the MSG landfill. However, the amount of surface defilements accounted for 27.3 wt.% and, thus, the real concentration of the non-ferrous metals was adjusted to about 3.5 kg per Mg.

In the fine fractions there was a dominant presence of Al and Cu scraps with amounts of about 44.5 wt.% and 33.4 wt.%, respectively. The alloying content in the Al scrap was negligible, as this material was mostly derived from packaging and foils, which tend to employ high purity Al. The particle size ranges 90-30 mm and 10-4.5 mm were mostly composed of Al packaging and foils, which could be successfully freed from surface defilements and, thus, could yield high grade Al. Additionally, most of the Pb and Zn scraps was detected in the fine fractions, from which Pb-scrap accounted for respective amounts of 5.5 wt.% and 5.2 wt.% of the total recovered non-ferrous metals from the MSG landfill. The analyzed samples of Pb-scrap presented small amounts of surface defilements, suggesting suitability for direct marketing, while those of Zn-scrap showed the presence of other metals and polymers that could significantly hinder their marketability.

Moreover, the fine fractions showed a higher content of surface defilements than the coarse fractions. The amount of surface defilements increased as the particle size decreased, which can be corroborated by the results of the characterization study of the fine fractions obtained in the scientific article no. 4. However, both fractions presented similar trends regarding the distribution of surface defilements according to the type of metal.

The particle size range 10-4.5 mm of the fine fractions showed amounts around 40-50 wt.% of surface defilements, which was also the particle size range with the highest amounts.

Research question: To what extent could the ferrous and non-ferrous metals recovered from the fine fractions of the Mont-Saint-Guibert landfill be valorized and what would be the main challenges?

The net recovered amount of total metals (ferrous + non-ferrous metals) from the MSG landfill accounted for about 2.9 wt.%, from which ca. 16.5 wt.% corresponded to non-ferrous metals. From the total amount of non-ferrous metals around 74 wt.% originated from the fine fractions.

According to the results of this study, the overall and average metal concentrations of the non-ferrous metals recovered from the fine fractions account for 72.4 wt.%, 71.9 wt.% and 56.5 wt.% in the particle size ranges 90-30 mm, 30-10 mm and 10-4.5 mm, respectively. These materials presented significant amounts of surface defilements composed of organic and inorganic matter, from which most of them corresponded to organic matter and which were strongly bound to the non-ferrous metals. However, most of the recovered non-ferrous metals did not show severe signs of deterioration and/or oxidation. Nonetheless, the implementation of a thorough cleaning process would be needed in order to enhance the valorization of the recovered non-ferrous metals from the fine fractions, since the specifications of the metal recycling industry can be very strict in terms of alloying and impurities content, and the prices of these metals vary significantly according to their quality.

To this end, the application of the thermal de-coating process employed by the Al industry was proven useful to remove most of the surface defilements from the recovered non-ferrous metals in raw state and, thereby, to raise their quality and revenue potential. This means that the non-ferrous metals output from the mechanical processing would need to be further separated according to type of metal, which is to be associated with additional costs and could hence affect the economic feasibility of (E)LFM.

Therefore, an appropriate economic and technical assessment is to be performed in order to identify the most adequate approach to maximize the profitability of the recovered non-ferrous metals.

12.9 Scientific Article No. 9

The produced combustibles and inert fractions by means of the tested dry mechanical approach of the fine fractions of the MSG landfill were subjected to laboratory analyses in order to determine and analyze their main physico-chemical characteristics, and evaluate their suitability and extent of valorization as alternative fuel (e.g. RDF/SRF) and substitute for construction aggregates (e.g. sand and gravel), respectively. The samples of both fractions were analyzed per particle size range (i.e. 90-30 mm, 30-10 mm and 10-4.5 mm) and state (i.e. the owc and dry states).

The median original proportions according to particle size range, i.e. 90-30 mm, 30-10 mm and 10-4.5 mm, in which the combustibles fractions were produced were around 38 wt.%, 41 wt.% and 21 wt.% in the owc state, respectively. In the dry state the median amounts correspond to about 47 wt.% for the particle size range 90-30 mm, 31 wt.% for 30-10 mm and 22 wt.% for 10-4.5 mm. In turn, amounts of approx. 41 wt.%, 42 wt.% and 17 wt.% account for the respective median proportions of the particle size ranges 90-30 mm, 30-10 mm and 10-4.5 mm of the inert fractions in the owc state, whereas ca. 42 wt.%, 36 wt.% and 22 wt.% correspond to those in the dry state, respectively.

The laboratory results of the inert fractions reveal that they are mainly composed of silicon dioxide (SiO_2), followed by aluminium oxide (Al_2O_3), calcium oxide (CaO), iron oxide (Fe_2O_3) and sodium oxide (Na_2O), and that chemically there were no significant differences between the owc and dry states. Furthermore, the results of the laboratory analyses of both the combustibles and inert fractions revealed that the quality of those fractions decreased with the decrease in particle size, as well as that the fractions in the owc state presented a lower quality than those obtained in the dry state. This can be explained by the facts that the amount of surface defilements and agglomerates increased as the particle size decreased, a larger amount of impurities was associated with the owc state and impurities can be associated with organic and inorganic pollutants. Results suggest moreover that the overall quality of both combustibles and inert fractions could be improved by mixing the particle size ranges in the proportions in which they were produced.

Research question: To what extent could the combustibles and inert fractions recovered from the fine fractions of the Mont-Saint-Guibert landfill be valorized and what would be the main challenges?

Total amounts of 12.5 wt.% and 9.0 wt.% of the combustibles fractions were obtained from the mechanical processing of the fine fractions from the MSG landfill case study in the owc and dry states, respectively.

From an overarching perspective, the total of the recovered combustibles in both states could be valorized as SRF in the EU in (co-)incineration plants, power plants and cement plants according to the EN 15359:2011. However, different additional regulations may apply among the EU member states and, hence, the extent of their valorization in WtE schemes is strongly dependent on national and local legislation. For example, taking as a reference the Waste Incineration Ordinance (AVV) in Austria, this material can only be incinerated in waste treatment plants and may not be co-incinerated in power plants, since the concentrations of As, Cd, Co, Hg and Pb in certain samples exceeded the established limit values. Hence, the plasma gasification process proposed in the NEW-MINE project might result to be a much more appealing WtE valorization scheme for recovered combustible materials from the fine fractions of ELFM.

In turn, the obtained quantities of the inert fractions accounted for 35.5 wt.% in the owc state and 37.2 wt.% in the dry state. To this day there is no overarching regulation applicable to recovered inert materials from (E)LFM in the EU and, thus, these materials are solely subject to national and local legislation on recycling building materials. In Austria this type of material would need further treatment in order to be used as substitute for construction aggregates, according to the Recycling Building Materials Ordinance (RBV) in that country, since in some samples the amounts of hydrocarbons, Cd, Pb, Zn, $NH4^+$ and anionic surfactants did not observe the limit values.

Therefore, in order to enable the WtM and WtE valorization of the combustibles and inert fractions recovered from the fine fractions of (E)LFM suitable regulations need to be created, and appropriate valorization schemes need to be further developed at EU level.

12.10 Scientific Article No. 10

In order to study the potential for material recovery from the obtained fine fractions <4.5 mm from the dry mechanical processing of the fine fractions <90 mm of the MSG landfill, the fine fractions <4.5 mm were subjected to further mechanical processing.

The mechanical processing approach tested in this study corresponded to a dry process (according to the results of the characterization of the fine fractions from the MSG landfill in the research article no. 5) and consisted of particle size classification steps and a dry surface cleaning process by means of surface attrition. The dry state in this study corresponds to an average water content of 1.5 wt.%. The particle size classification steps divided the material into the particle size ranges 4.5-1.6 mm, 1.6-0.5 mm, 0.5-0.18 mm and <0.18 mm, whereas the surface cleaning process was applied to the coarsest particle size ranges 4.5-1.6 mm and 1.6-0.5 mm.

The initial hypothesis was that the problematic elements and compounds (i.e. pollutants) would be present as very small particles and, thus, most of them would be found in the smallest particle size ranges, which could attach to the surface of coarser particle sizes in the form of surface defilements. The latter can significantly decrease the quality of a material in view of WtM valorization schemes; hence, this investigation aimed at the removal of surface defilements in the coarsest particle size ranges in order to study their valorization potential, as well as the particle size distribution and the physical and chemical characteristics of the different particle size ranges.

The mineralogical composition of the particle size ranges 0.5-0.18 mm and <0.18 mm was determined and discussed, and the effectivity of the employed mechanical processing approach was also evaluated.

The concentration of pollutants in a certain particle size range by means of particle size classification and a surface cleaning process was not possible due to the nature and form in which the pollutants were present. However, it was confirmed that the leachability of these fractions is strongly related to their mineralogical composition, since several host phases for low-leaching elements were identified.

Research question: How could the fine fractions <4.5 mm of the Mont-Saint-Guibert landfill be further processed to enable material recovery, what are the main characteristics of the produced fractions and to what extent could they be valorized?

The fine fractions <4.5 mm of the MSG landfill, which accounted for an average amount of 42.9 wt.% in the dry state of the total quantity of the fine fractions <90 mm, were mostly composed of humified organic and weathered inorganic matter. Ferrous and non-ferrous metals and combustible materials were depleted in these fractions. Total average amounts of 11.7 wt.%, 9.5 wt.%, 14.3 wt.% and 7.4 wt.% were obtained of the particle size ranges 4.5-1.6 mm, 1.6-0.5 mm, 0.5-0.18 mm and <0.18 mm in the dry state, respectively.

The results of the chemical laboratory analyses revealed that the fine fractions <4.5 mm were mainly constituted by SiO_2 (ca. 70 wt.%), followed by smaller amounts of CaO (ca. 5 wt.%), FeO_3 (ca. 4 wt.%) and Al_2O_3 (ca. 4 wt.%). Additionally, these fractions showed no clear trend regarding the increase or decrease of heavy metal contents according to particle size. The pseudo-total contents of organic carbon, Cd, Cu, Hg, Pb and Zn exceeded the Austrian limit values for the production of soil substitutes from wastes, while the limit values of the leachable contents are expected to stay below the limit values, since the results could not be directly compared to the ordinances due to differences in dissolution ratios. Elevated concentrations of Cd and Pb could be explained by the fact that glass was not removed from these fractions in the mechanical processing.

The mineralogical analyses unveiled that the particle size ranges 0.5-0.18 mm and <0.18 mm consisted mainly of quartz (ca. 70-80 wt.%), calcite (10 wt.%), feldspars (ca. 10 wt.%) and minor amounts of kaolinite, illite, siderite and gypsum, without any significant discrepancies between both particle size ranges. Hence, the fine fractions <4.5 mm would need to undergo further treatment to enable the envisaged type of valorization scheme in Austria. However, the removal of Pb- and Zn-containing phases remains highly challenging to date. Moreover, no overarching regulation at EU level exists to this day and, thus, the valorization of these fractions strongly depends on national and local legislation. In countries in which only leachable contents are regulated, the valorization of these fractions seems more realistic.

The tested dry mechanical processing approach successfully decreased the amount of surface defilements on the processed particle size ranges: nevertheless, as the pollutants were not exclusively present in the form of surface defilements, the effects of the mechanical processing on improving the quality of the particle size ranges 4.5-1.6 mm and 1.6-0.5 mm were marginal. In turn, alternative routes for the WtM valorization of these fractions are to be considered and further studied, such as landfill liner or other constituent in an “aftercare-free” landfill, in which the presence of heavy metals and other organic and inorganic pollutants might not completely hinder their further utilization.

13 DISCUSSION

The fine fractions from landfill-mined waste belong to the most important challenges faced by (E)LFM, as these fractions typically account for the largest share of the excavated material and present difficult characteristics for traditional material processing techniques and valorization routes (Hernández Parrodi et al., 2018a). Because of the latter, the fine fractions have been largely discarded in previous LFM projects: hindering the whole economic and environmental feasibility of those projects and calling into question the whole purpose of future (E)LFM activities (Bhatnagar et al., 2017; Hernández Parrodi et al., 2018b; Münnich et al., 2013; Wolfsberger et al., 2015). Therefore, it is of decisive relevance to include the fine fractions into the scope of the material processing schemes and valorization strategies of every (E)LFM project, in order to enable material and energy recovery from them, as well as to maximize land reclamation and minimize aftercare costs (Hernández Parrodi et al., 2018b). Land reclamation is commonly one of the main drivers of (E)LFM projects, since it can represent the most relevant source of immediate revenue (Esguerra et al., 2019; Hermann et al., 2014; Hernández Parrodi et al., 2018b; Hernández Parrodi et al., 2019b; Krook et al., 2012). To this end, the fine fractions need to be thoroughly studied and the latest material processing methods and know-how need to be put to test, which was the main purpose of the present doctoral thesis.

The thesis at hand demonstrated that the landfill-mined waste of the MSG landfill can be pre-processed down to a particle size of 90 mm by means of a robust ballistic separator directly after excavation (García López et al., 2019). The produced fine fractions <90 mm accounted for about 77 wt.% of the total pre-processed excavated material and presented an overall median water content and bulk density of around 27 wt.% and 810 kg/m^3, respectively (Hernández Parrodi et al., 2019a). Furthermore, the material characterization of the fine fractions <90 mm was performed in both the raw (i.e. with the original median water content of 27 wt.%) and dry states in order to study the influence of the water content on the main characteristics of the material (e.g. bulk density, material composition and particle size distribution), and on the interactions among them. The results of that study, Hernández Parrodi et al., 2019a, showed that the water content plays an extremely important role in the material characterization and material processing, since it has a direct influence on the results regarding material composition, bulk density and particle size distribution, as well as in the effectivity and efficiency of mechanical processing steps. Thus, the water content is to be adjusted according to the selected mechanical processing approach (i.e. dry, wet or combined mechanical processing) for best results, which in turn is to be chosen depending on the foreseen WtM and WtE valorization schemes.

The material characterization of the fine fractions <90 mm in the dry state revealed that a median share of 51.8 wt.% corresponded to the fine fractions <10 mm, while the fine fractions 90-10 mm were composed of 32.4 wt.% inert, 8.0 wt.% combustibles, 3.8 wt.% agglomerated fines <10 mm, 1.3 wt.% total metals (ferrous and non-ferrous metals) and 0.9 wt.% unidentified materials (Hernández Parrodi et al., 2019a). This information showed that the fine fractions <90 mm could be separated into subfractions according to their physico-chemical properties, such as particle size, shape, density and composition, by means of further state-of-the-art mechanical processing methods (Hernández Parrodi et al., 2019c). Particle size classification, metal extraction, density separation and NIR sorting methods could be used to recover ferrous and non-ferrous metals and combustible and inert materials from the fine fractions <90 mm, as well as to produce a sol-like fraction (Hernández Parrodi et al., 2019c). Therefore, the previous information was used to design the mechanical processing approach to be employed and select the valorization schemes to be pursued in the MSG landfill case study (Hernández Parrodi et al., 2019a). The following fractions and the potential WtM and WtE valorization routes were envisaged for the fine fractions <90 mm (Hernández Parrodi et al., 2019a; Hernández Parrodi et al., 2019c):

- Ferrous and non-ferrous metals for recycling; WtM
- Combustible materials for the production of RDF; WtE
- Inert materials for the production of a substitute for construction aggregates; WtM
- Soil-like fraction for the production of a substitute for soil in construction applications; WtM

The studied mechanical processing approach in this thesis consists of dry methods. This type of approach was selected because wet mechanical processing methods, although having been associated with a high effectivity and efficiency, as well as with high quality outputs, tend to be much more complex systems and, thus, are significantly more costly to acquire and operate than most dry processing mechanical methods (Bunge, 2012; Krüger et al., 2016; Martens and Goldmann, 2016). Moreover, one of the main target outputs of the selected mechanical processing approach was RDF, which as all other target outputs (i.e. ferrous and non-ferrous metals, and inert materials and soil-like fraction) of the mechanical processing is best handled and, if the case, commercialized in dry state. In addition, the original median water content of the fine fractions (i.e. 27 wt.%) was relatively low, in comparison with previous investigations (Bhatnagar et al., 2017; Gutiérrez-Gutiérrez et al., 2015; Hull et al., 2005; Kurian et al., 2003). It is important to mention that the implementation of a dry mechanical processing approach is to be associated with significant additional resources (i.e. energy and time), which may increase the overall processing costs. Nevertheless, most of the output fractions would need a drying or moisture adjustment process after a wet mechanical processing before commercialization as well. Additionally, it is worth noting that the implementation of the owc state (i.e. water content of 15 wt.%) and the utilization of the recovered RDF to partially power the moisture adjustment process could substantially contribute to decrease the additional energy demand of a dry mechanical processing.

The mechanical processing of the fine fractions <90 mm of the MSG landfill was divided into 2 approaches: one for the fine fractions 90-4.5 mm (Hernández Parrodi et al., 2019c) and another one for the fine fractions <4.5 mm (Vollprecht et al., 2020). According to the characteristics of the fine fractions <90 mm (Hernández Parrodi et al., 2019a), the selected mechanical processing approach for the fine fractions 90-4.5 mm was tested in the owc and dry states, while the one for the fine fractions <4.5 mm was solely carried out in the dry state. The mechanical processing of the fine fractions 90-4.5 mm in the dry state showed higher effectivity and efficiency than in the owc state, as well as a higher quality in the output fractions. Additionally, the mechanical processing of the fine fractions 90-4.5 mm in the dry state presented higher material losses in the form of dust and fine-sized particles, and was associated with a higher energy demand. However, the differences between the mechanical processing of the fine fractions 90-4.5 mm in the owc and dry states in terms of effectivity, efficiency and outputs quality were slight and did not significantly interfered with the targets of the mechanical processing approach, nor with the potential valorization routes of the produced outputs. In turn, the owc state resulted to be effective in substantially reducing the material losses and energy demand of the mechanical processing. Moreover, the results of the mechanical processing of the fine fractions 90-4.5 mm showed that the quality of the output fractions presented a clear tendency to decrease with the decrease in particle size, since an increasing amount of impurities and surface defilements was identified as the particle size decreased. Furthermore, the decrease in particle size adversely affected the effectivity and efficiency of the mechanical processing methods, especially the NIR sorting and metal extraction methods.

The combustible fractions recovered from the fine fractions 90-4.5 mm (Hernández Parrodi et al., 2020), which accounted for median total amounts of about 12.5 wt.% in the owc state and 9.0 wt.% in the dry state, with respect to the total amount of fine fractions <90 mm, complied with the specifications set by the EN 15359:2011 for the production of SRF in Europe. However, the combustible fractions may be subjected to further national and local regulations as well. For example, in Austria these fractions showed problematic pseudo-total contents of As, Cd, Co, Hg and Pb according to the Waste Incineration Ordinance (AVV). Hence, the concentrations of those heavy metals would need to be reduced in order to use the recovered combustible fractions in co-incineration plants, power plants and cement plants in Austria. As reported by Viczek et al., 2019, high concentrations of As, Cd, Co, Hg and Pb in MSW and IW can be associated with the presence of glass, metal alloys, ceramics, textiles, certain plastics (e.g. PVC, LDPE and HDPE), electronic waste and batteries. Therefore, the concentrations of the previously mentioned problematic heavy metals could be reduced by removing certain types of materials, e.g. by means of NIR (Küppers et al., 2019; Pieber et al., 2012; Vrancken et al., 2017), XRF (Aldrian et al., 2015; Turner and Filella, 2017) or manual sorting. However, attention is to be paid to the implications of such additional material processing on the characteristics of the RDF, such as CV and concentrations of other elements and compounds (Pieber et al., 2012; Viczek et al., 2019), as well as to the effects on the capital expenditures (CAPEX) and operating expenses (OPEX) of the mechanical processing. Moreover, adequate removal methods for certain materials, e.g. composite materials, might not be yet available in large scale (Viczek et al., 2019).

Furthermore, the valorization of the recovered combustible fractions from landfill-mined waste could be best performed in the plasma gasification process proposed in the NEW-MINE project (Hernández Parrodi et al., 2019b), which due to its robustness and flexibility could deal with the defying characteristics of this type of fractions (Zaini et al., 2019; Zaini et al., 2017), while immobilizing the problematic elements and compounds in a vitrified byproduct and producing high quality energy carriers, such as hydrogen and methane (Jones et al., 2010; Jones et al., 2013; Jones and Tielemans, 2010). Also, the obtained vitrified byproducts could be upcycled into high value-added products, such as synthetic polymers (Ascensão et al., 2019; Machiels et al., 2017) and glass-ceramics (Rabelo Monich et al., 2019; Rabelo Monich et al., 2020). In this way, additional and relevant sources of revenue could be created to promote the viability of ELFM projects and the material and energy recovery rates would be increased. Moreover, as discussed in Viczek et al., 2020, the valorization of the combustible fractions as SRF in the production of cement is not solely to be regarded as the recovery of energy, but as material recovery as well, since about 13.5-17.6 wt.% DM of the SRF is incorporated in the form of ash into the produced clinker, which in turn is used to produce cement. Similarly, a significant share of the ash content of the combustible fractions would end up in the vitrified byproduct of the plasma gasification process, which eventually would be transformed into synthetic polymers and glass-ceramics.

On an EU level, there is no overarching regulation applicable to the production of a substitute for construction aggregates with the inert fractions recovered from the fine fractions 90-4.5 mm for the time being and, thus, the extent of the valorization of these fractions is largely dependent upon national and local regulations (Hernández Parrodi et al., 2020). Taking Austria as an example once more reveals that the recovered inert fractions cannot be used as recycled construction aggregates according to the Recycling Building Materials Ordinance (RBV), unless their pseudo-total contents of hydrocarbons, Cd, Pb and Zn and their leachable concentrations of ammonium-N and anionic surfactants are reduced through further treatment, and the limit values for those parameters are met. These fractions represented median total amounts of around 35.5 wt.% and 37.2 wt.% in the owc and dry states, respectively, of the total amount of the fine fractions <90 mm. Therefore, holistic regulations and suitable valorization routes for the recovered inert fractions from landfill-mined waste need to be developed, in order to enable the reincorporation of this type of materials into the production cycle of new materials. For example, the employment of these fractions for the production of non-structural concrete, which could be used in applications such as walls, facades and fillings, could be an alternative WtM route in which the problematic elements and compounds could be immobilized to a great extent.

It is important to note that both the recovered combustible and inert fractions from the fine fractions of (E)LFM are likely to be valorized together with those recovered from the coarse fractions. The latter frequently present better quality than that of the fine fractions and account for a considerable amount of the processed landfill-mined waste. Thus, the overall quality of the resulting combustibles and inert fractions might be significantly improved in this way, which might lead to the compliance of the limit values. Nevertheless, the effects of the joint valorization of the recovered combustible and inert fractions from the fine and coarse fractions were not included into the scope of the present thesis.

Regarding the ferrous and non-ferrous metals, respective median total amounts of about 0.9 wt.% and 1.4 wt.% of ferrous metals were recovered in the owc and dry states, while 0.4 wt.% and 0.3 wt.% of non-ferrous metals were obtained with respect to the total amount of fine fractions <90 mm. Whereas most of the total amount of the ferrous metals can be expected to be eligible for recycling by the metal recycling industry, about 70 wt.% DM of the total amount of the non-ferrous metals corresponded to potentially recyclable metal (Lucas et al., 2019). This information demonstrates that both ferrous and non-ferrous metals can be recovered from the fine fractions of landfill-mined waste and that, although rather low, most of their shares could be suitable for recycling purposes.

The mechanical processing approach of the fine fractions <4.5 mm consisted of particle size classification and surface cleaning steps (Vollprecht et al., 2020), which due to the determined characteristics (sc. particle size distribution and water content) of the fine fractions <90 mm needed to be carried out in dry state. The fine fractions <4.5 mm corresponded to a median total amount of around 42.7 wt.% in the dry state of the total amount of the fine fractions <90 mm of the landfill-mined waste. These fractions account for the largest share of the different outputs of both the mechanical processing of the coarse fractions (i.e. ≥90 mm) and the fine fractions (i.e. <90 mm) of the MSG landfill. The results of the selected approach show that the composition of the fine fractions <4.5 mm mainly corresponded to that of the average composition of earth´s crust, although with higher amounts of SiO_2 and lower amounts of Al_2O_3. Additionally, the results of the solid matter laboratory analyses and leaching tests reveal that there were no significant variations regarding the distribution of pollutants among the different particle size ranges (i.e. 4.5-1.6 mm, 1.6-0.5 mm, 0.5-0.18 mm and <0.18 mm), which opens the possibility to fully implement land reclamation at the old part of the landfill of this case study (i.e. the MSG landfill), provided that a suitable application or valorization route can be found in Belgium for these fractions. In summary, the pseudo-total contents of TOC and heavy metals (i.e. Cd, Cu, Hg, Pb and Zn) for certain samples exceeded the Austrian limit values for the recycling of excavated soil (Federal Ministry for Sustainability and Tourism, 2017) and excavated soil landfills (Federal Ministry for Agriculture, Forestry, Environment and Water Management, 2008), while the leachable contents of heavy metals were well below the limit values set in the ÖNORM S 2122-2, as the majority of the heavy metals was proven to be tightly bound in low-soluble mineral phases or strongly adsorbed to mineral surfaces. The tested further mechanical processing approach did not suffice to decrease the concentrations of those problematic elements and compounds of the coarser particle size ranges (i.e. 4.5-1.6 mm and 1.6-0.5 mm) by means of particle size classification and surface cleaning to such an extent that the Austrian limit values were met, nor to concentrate pollutants in the finest particle size ranges (i.e. 0.5-0.18 mm and <0.18 mm). Thus, the fine fractions <4.5 mm from the MSG landfill could be valorized as substitute for soil in construction applications in countries in which only leachable contents are regulated, but these fractions would need further treatment in those countries in which pseudo-total contents are also taken into account.

Further processing methods, such as wet, chemical and mineralogical treatments, could be employed to decrease the amount of the problematic elements and compounds in the fine fractions <4.5 mm: however, these methods are associated with much more complex processes, which in turn require higher CAPEX and OPEX. Therefore, alternative applications, such as landfill liner and cover layer, or for the productions of low quality vitreous/refractory materials, in which the pseudo-total contents of these fractions do not pose a risk to the wellbeing of the environment and living beings, need to be considered as potential valorization routes and suitable directives are to be developed in order to regulate and promote their application.

Nonetheless, it should be emphasized that the previously mentioned potential WtM applications (i.e. synthetic polymers, glass ceramics, non-structural concrete, landfill liner/cover layer and low quality vitreous/refractory materials) for the recovered inert materials and soil-like fractions from the fine fractions, as well as for the residues of the thermo-chemical valorization of the combustible fractions, are to comply with the applicable norms, standards and any additional criteria established by the relevant scientific, industrial and governmental institutions. Furthermore, most of the studies and tests performed within the NEW-MINE project were carried out by means of laboratory-, small- and pilot-scale equipment, and are related to a specific case study (i.e. the MSG case study). Therefore, much attention is to be paid to several factors when transposing the methods and findings of the NEW-MINE project for the purpose of full-scale applications, since results can significantly differ in large-scale equipment and the upscaling implications are yet to be investigated.

In general, the employment of innovative and sophisticated treatment methods to remove most of the pollutants from the different fractions recovered from landfill-mined waste, in order to unlock a wide variety of WtM and WtE valorization routes, seems unlikely with the current market and legislative conditions. This is the case because present-day prices for primary raw materials and heterogeneous and exclusive regulations in the waste management sector remain to be unsurmountable obstacles for (E)LFM, as well as that landfilling the soil-like fractions is often less costly than their further processing, and long-term environmental and health impacts of legacy landfills and dumpsites are frequently underestimated or not considered at all in the economic assessment of such projects. Rather than a method focused to mainly obtain revenues from land reclamation and secondary resources in the form of materials and energy, (E)LFM should be seen as an alternative to mitigate environmental pollution and address the issue of historic landfills and dumpsites, which are more of an obligation before our future generations and are linked to presently unknown but, nevertheless, very high long-term costs as well. This misconception has made (E)LFM strongly dependent on market conditions and, thus, on its economic feasibility. However, this situation could be temporarily addressed through the implementation of adequate policy instruments, such as regulations, taxes and subsidies, that promote the implementation of (E)LFM. Therefore, the increasing market prices of primary raw resources, the development of a sound regulatory framework for secondary raw materials, and the raising public awareness will eventually pave the way for the development of more complex and effective processing technologies that can enable full material and energy recovery from landfill-mined waste (Hernández Parrodi et al., 2020).

In the meantime, specific WtM and WtE valorization routes, such as plasma gasification for the combustible fractions and the production of non-structural concrete for the inert fractions and low quality vitreous materials with the finest fractions, that can deal with significant concentrations of pollutants are to be employed in priority landfills and dumpsites, such as those located at flood areas, in order to avoid potential future environmental disasters. Furthermore, re-landfilling of certain subfractions of the fine fractions, possibly after inertization, stabilization and compaction, as a pre-treated monolithic material might be an interesting alternative to significantly decrease landfill aftercare expenditures, since long-term landfill gaseous and leachate emissions can be significantly reduced in this manner (Hjelmar et al., 2006; Hung et al., 2009; Radenkova-Yaneva et al., 1995; Scharff et al., 2011; Vollprecht et al., 2020). Therefore, the resulting “aftercare-free” monolithic landfill might represent a safe final sink for the fine fractions and enable land reclamation, and the recycling of other materials (Vollprecht et al., 2020). However, the implications of such alternative are to be further investigated and subjected to a technical, socio-economic and environmental assessment.

14 CONCLUSION

The fine fractions, typically defined as the material with a particle size <60 mm to <10 mm depending on the project, are one of the most critical challenges faced by (E)LFM, as these fractions normally account for the largest share of the landfill-mined waste (40-80 wt.%) and are commonly directed back into the landfill without any material or energy recovery from them. This has been the case up to now since the fine fractions usually present challenging characteristics for conventional waste treatment techniques, such as their relatively high water content (15-60 wt.%) and pollutants (e.g. heavy metals, hydrocarbons, PAHs and PCBs) concentrations, coupled with their fine particle sizes.

In the case study of the MSG landfill, the fine fractions corresponded to the material <90 mm obtained through ballistic separation directly after excavation. These fractions represented about 77 wt.% of the total amount of the processed excavated landfill waste (~370 Mg) and had a median water content of 27 wt.% and a median bulk density of 810 kg/m^3. The fine fractions <90 mm were subjected to two dry mechanical processing approaches (i.e. one for the fine fractions 90-4.5 mm and another for the fine fractions <4.5 mm). Both dry mechanical processing approaches proved to be successful in separating the fine fractions into the intended output fractions in an effective and efficient manner. The intended outputs consisted of combustibles and inert fractions, ferrous and non-ferrous metals and soil-like material (i.e. fine fractions <4.5 mm). From the total amount of the fine fractions <90 mm around 9.0 wt.% combustibles, 37.2 wt.% inert, 1.4 wt.% ferrous metals, 0.3 wt.% non-ferrous metals and 42.7 wt.% fine fractions <4.5 mm were obtained in dry state.

The results of the laboratory analyses of the combustibles fractions revealed that these fractions could be valorized as SRF in the EU according to the EN 15359:2011. However, stricter national and local specifications may apply among EU member states: impeding or limiting the valorization of these fractions. Therefore, in contrast to conventional (co-) incineration of alternative fuels, plasma gasification/pyrolysis might offer an attractive alternative WtE valorization route for the recovered combustible fractions from the fine fractions of landfill-mined waste. In turn, the results of the laboratory analyses of the inert fractions unveiled that in Austria these fractions would need to undergo further treatment in order to be used as substitute for construction aggregates. However, there is no overarching regulation applicable for this type of material at an EU level yet in place and, hence, the extent of valorization of these fractions solely depends on national and local legislation as well. Most of the recovered ferrous and non-ferrous metals were considered to be suitable for recycling purposes, as non-ferrous metals showed acceptable overall metal concentrations and the ferrous metals presented similar characteristics to those valorized in previous studies. Therefore, it can be said that the fine fractions can be a source of significant amounts of ferrous and non-ferrous metals.

The findings of the dry mechanical approach applied to the fine fractions <4.5 mm and the results from the laboratory analyses demonstrate that the potentially organic and inorganic pollutants cannot be sufficiently removed from the coarse particle size ranges and concentrated in the finer ones solely by means of particle size classification and surface cleaning processing steps. The leaching concentrations of most analyzed heavy metals were below the applicable Austrian limit values, and the results of pseudo-total contents and leaching tests reveal that there were no significant variations regarding the distribution of pollutants among particle size ranges. Therefore, land reclamation could be fully implemented at the old part of the MSG landfill, provided that a suitable application or valorization route for these fractions can be found, such as landfill cover layer or bottom liner, and that the applicable requirements for such applications can be met in Belgium. In general, all applicable norms, standards and any additional criteria established by the relevant scientific, industrial and governmental institutions are to be considered for a successful valorization of recovered materials from landfill-mined waste.

Furthermore, current market and regulatory conditions tend to render the (E)LFM process economics unfavorable, as in some cases prices of primary raw materials can be well below those of secondary raw materials, and recovered materials through (E)LFM are frequently left out of regulations, e. g. in the case of substitutes for construction aggregates and soil in construction applications. These circumstances hinder to a great extent the overall economic and environmental feasibility of (E)LFM. Therefore, to overcome these challenges the fine fractions need to be included in the scope of the material and energy recovery strategies of (E)LFM projects to the greatest extent possible, while the recovered materials from landfill-mined waste require to be integrated into WtM and WtE valorization routes, regulations and waste management programs. Additionally, the valorization/utilization of materials recovered through (E)LFM needs to be encouraged by transitory economic and political mechanisms (e.g. taxes and subsidies), which can promote the viability of (E)LFM projects while the gap between the practically possible and economically feasible is bridged. Moreover, the development of novel technologies that can produce materials with higher qualities and, thus, enable further material and energy recovery from landfill-mined waste strongly relies on investment from the private sector, which will definitively find (E)LFM more appealing if its business model is substantially improved.

In addition, the fine fractions are a well widespread issue across the entire waste treatment and recycling industry and, therefore, the results of the present thesis can serve the purpose of improving the approach with which the fine fractions have been addressed to this day, and developing guidelines and standardized procedures, which are already of high interest for the industry. The employed procedure in this research, which was only tested at pilot-, small- and laboratory-scale, proved to be successful in terms of separating the fine fractions into the intended fractions in an effective and efficient manner, as well as in terms of determining the most important properties of the fine fractions for the design of an appropriate processing approach. Therefore, it can be concluded that this procedure is worth testing at industrial-scale as a next step, in order to study the upscaling effects and implications on the technical, economic and environmental feasibility of (E)LFM in a more realistic way.

15 OUTLOOK ON FUTURE RESEARCH

It is certainly worth studying and testing whether the quality of the output fractions of the processing of the fine fractions of (E)LFM can be significantly improved through the application of alternative treatment techniques, such as wet, chemical and mineralogical methods, and thus determine if the most stringent criteria required by some member states of the EU can be met. Although these methods might seem largely unfeasible at present, they may become viable alternatives in the future, provided that they can meet the applicable quality specifications of their outputs and a competitive market for such products exists in the corresponding location.

An additional approach worth of research is the further development and, if necessary, the creation of suitable overarching WtM and WtE valorization schemes in terms of marketability and policy for recovered materials through (E)LFM in the EU. For example, to study in detail the environmental, economic and societal effects of the inclusion of recovered materials through (E)LFM into the market of secondary raw materials and those of the promotion of their utilization through the implementation of taxing and/or subsidizing mechanisms on primary raw materials, together with the facilitation of their use by the creation of inclusive regulations and guidelines. Such an approach could promote the economic feasibility of (E)LFM and attract private and public investment in innovation and further research on the fine fractions, since further research on the processing of the fine fractions is directed linked to and heavily relies on the extent of their real valorization, which nowadays is extensively hampered in the EU.

Also, an alternative valorization route for the recovered inert fractions from the fine fractions that should be further investigated is the production of non-structural concrete (e.g. for facades and fillings), in order to study if the main potentially problematic elements and compounds could be sufficiently immobilized in that way. As for the finest fractions of the fine fractions, the production of low quality glass/refractory products and a substitute for soil in construction applications (e.g. as filling material) should be studied in detail as well.

Nowadays, sanitary landfilling of the fine fractions is suggested to be the best option. This alternative is associated to research questions regarding the reduction of landfill aftercare in a significant manner, which might be achieved by compaction and inertization of the fine fractions as a pre-treated monolithic material prior to re-landfilling. Further research is needed regarding sustainable methods to reach this aim in order to guarantee long-term safety of the landfill. In this case, the release of the landfill from aftercare might be achieved to a certain extent, i.e. very low treatment and monitoring of landfill gas and leachate might still be necessary or even not at all. This “aftercare-free” monolith landfill scenario should be further investigated and assessed in the context of (E)LFM.

Last but not least, further research on cost-effective and energy-efficient alternatives to dry or decrease the water content of the fine fractions, as well as on the application of industrial-scale equipment, is of key relevance to upscale innovative dry mechanical processing approaches and improve the overall viability of (E)LFM.

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16.2 List of Abbreviations

2D	Two-dimensional
3D	Three-dimensional
a	Annum
AC	Ash content
Ag	Silver
Al	Aluminum
approx.	Approximately
ar	As received
As	Arsenic
AVAW	Chair of Waste Processing Technology and Waste Management
avg.	Average
Ba	Barium
°C	Degrees Celsius
Ca	Calcium

Cd	Cadmium
CETeM	Centre d´enfouissement Technique de Mont-Saint-Guibert
C.f.	Confer
Co	Cobalt
C&D/CDW	Construction and demolition waste
Cr	Chromium
Cu	Copper
DM.	Dry mass
ELFM	Enhanced landfill mining
e.g.	Exempli gratia (“for example”)
etc.	Et cetera (“and others”)
EU	European Union
Excl.	Excluding
Fe	Iron
Fe metals/FMs	Ferrous metals
g	Gram
GCV	Gross calorific value
Hg	Mercury
HIS	Hyperspectral imaging
IAR	Department of Processing and Recycling
i.e.	Id est (“that is”)
incl.	Including
IW	Non-hazardous industrial waste
K	Potassium
kg	Kilogram
L	Liter
LFM	Landfill Mining
m	Meter
m^2	Squared meter
m^3	Cubic meter
MBT	Mechanical biological treatment
mg	Milligram
Mg	Magnesium
Mg	Megagram
MJ	Megajoule
ml	Milliliter
mm	Millimeter
Mn	Manganese
Mo	Molybdenum
MSG	Mont-Saint-Guibert
MSW	Municipal solid waste
MUL	Montanuniversität Leoben

Na	Sodium
N.A.	Not available
NCV	Net calorific value
Ni	Nickel
NIR	Near-infrared
nm	Nanometer
Non-Fe metals/NFMs	Non-ferrous metals
(E)LFM	(Enhanced) landfill mining
p%	Percentage of particles
Pb	Lead
PE	Polyethylene
PET	Polyethylene terephthalate
PP	Polypropylene
PPC	Paper, paperboard and cardboard
pRDF	Potential refuse derived fuel
PS	Polystyrene
PSD	Particle size distribution
PVC	Polyvinylchloride
RDF	Refuse derived fuel
rpm	Revolutions per second
RWTH	Rheinisch-Westfälische Technische Hochschule
s	Second
SBS	Sensor-based sorting
sc.	Scilicet (“namely”)
SRF	Solid recovered fuel
t	Ton
TC	Total carbon
TOC	Total organic carbon
WtE	Waste-to-energy
WtM	Waste-to-material
WC	Water content
Wt.%	Percentage based on weight
XRF	X-ray fluorescence
Zn	Zinc
<d.l./b.d.l.	Below detection limit

16.3 Figures