

LANDFILL MINING: A REVIEW OF THREE DECADES OF RESEARCH

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Abstract

Landfills have historically been seen as the ultimate solution for storing waste at minimum cost. It is now a well-established fact however that such deposits have related implications such as long-term methane emissions, local pollution concerns and limitations on urban development. Landfill mining has been suggested as a strategy to address such resource and pollution problems and in principle means the excavation, processing, treatment and/or recycling of deposited materials. This study involves a literature review on landfill mining covering an analysis of trends, objectives and research topics in 39 papers published during the period 1988–2008. The results show that so far landfill mining has primarily been seen as a way to solve traditional waste management issues such as lack of landfill space or facilitation of final closure and remediation of waste deposits. Although most initiatives also have involved some effort to recover deposited resources (primarily cover soil material), such constituents have been largely secondary. Typically, simple soil excavation and screening equipment have therefore been applied, often demonstrating moderate performance in obtaining marketable recyclables. Several worldwide changes and recent research findings however indicate the emergence of a new perspective on landfills as future reservoirs for resource extraction. Although the potential of this approach appears gigantic, it is argued that facilitating implementation also involves a number of challenges in terms of technology innovation, concepts for realization and frameworks for evaluating economic and environmental performance.

Keywords

Waste, Conservation of landfill space, Remediation, Resource recovery, Future research

1. Introduction

In many regions of the world, landfills have long been seen as a final way to store waste at minimum cost. Nowadays, however, it is a well-known fact that such practices have a number of related implications (Daskalopoulos et al., 1997). Apart from that refined natural resources, in which materials and energy have been invested, are wasted, degradation of organic waste in such deposits generates long-term methane emissions contributing to global warming (Mor et al., 2006; Sormunen et al., 2008). Landfills, especially old ones lacking modern environmental technology, are also well-known sources for local pollution due to leaching of hazardous substances (Flyhammar, 1997). Furthermore, space issues have become increasingly important, especially in densely populated areas, where the location of such deposits sometimes interferes with city expansion (Zhao et al., 2007). In many parts of the world, however, landfilling is still the most common waste disposal method (Eurostat, 2009; Kollikkathara et al., 2009). Even in countries which have developed systems for waste treatment and recycling, this option has often remained important or at least still was as recently as a decade or so ago. Most regions therefore involve a large number of old and/or still operational landfills, in which vast amounts of obsolete materials and products have been accumulated over time, some of them more valuable than others (Lifset et al., 2002; Zhao et al., 2007).

Landfill mining has been proclaimed as an innovative strategy to address such implications related to waste deposits (Dickinson, 1995; Hogland, 2002). According to the Oxford Dictionary of English, “landfill” means *“the disposal of waste material by burying it”* or *“a place or process for a disposal of non-hazardous waste, based on burying it in the ground then compacting it to reduce the volume and finally covering it with soil and landscaping it to look like part of the surrounding land”*. The meaning of the word “mining” is, according to the same dictionary, *“the removal of minerals (such as coal, gold or silver) from the ground”* or *“the process of extracting solid natural resources from the shallow parts of the Earth’s crust”*. Combining these definitions, landfill mining could be described as *“a process for extracting minerals or other solid natural resources from waste materials that previously have been disposed of by burying them in the ground”*.

This study involves a literature review on landfill mining covering an analysis of trends, objectives and topics in 39 research papers published during the period 1988–2008. The overall aim is to assess state-of-the-art knowledge in order to identify key challenges for realization of this strategy in the years to come.

2 Landfill mining initiatives over time

According to Savage et al. (1993), landfill mining was first introduced in Israel in 1953 as a way to obtain fertilizers for orchards, but this remained the only reported initiative for several decades. In the 1990s, however, interest in this strategy increased, which is also reflected in the 39 reviewed papers, of which almost 70% originate from this decade, most from the period 1995–2000, Figure 1. Approximately 50% of these papers are from the U.S, while the remainder have been conducted in European (30%) or Asian (20%) contexts.

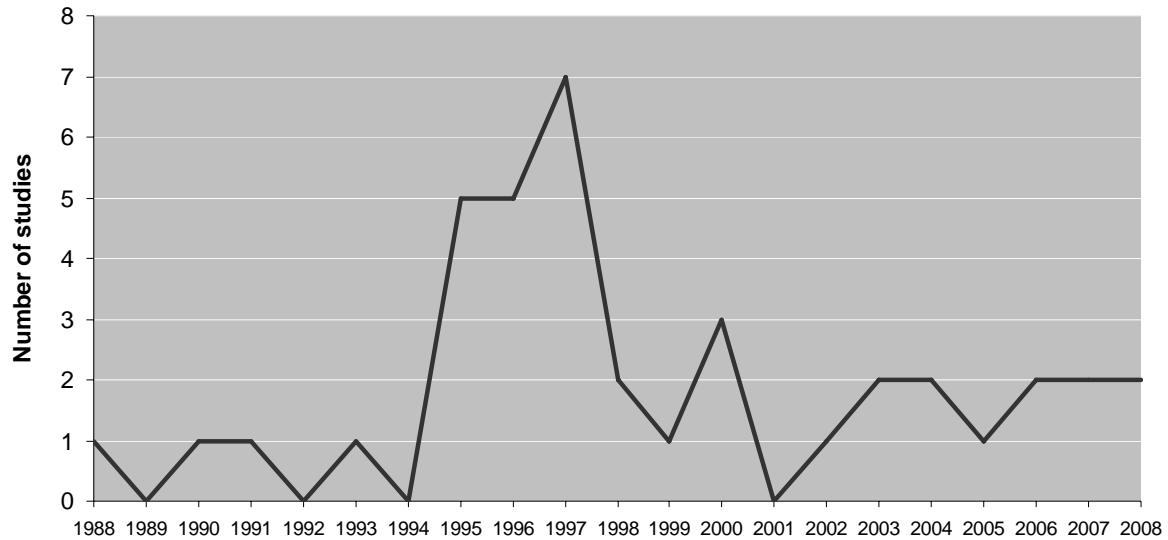


Figure 1. Research intensity on landfill mining over time presented as number of published papers per year. The total number of papers included in the figure is 39.

In the U.S., one of the most important drivers for this revival of interest in landfill mining during the 1990s was, either directly or indirectly, stricter environmental legislation. Such regulations forced many landfills to close down and also involved tougher requirements on final closure and post management, e.g. long-term monitoring of pollutants (Spencer, 1990; Richard et al., 1996a; 1996b). This took place in a time when landfilling was still by far the most commonly applied waste disposal method in the country and getting permission to develop new landfills was becoming increasingly difficult, primarily due to strong public opposition. Excavation, processing, treatment and recovery of landfilled materials then emerged as a promising strategy to solve the increasing shortage of landfill void capacity and to reduce or postpone costs related to final closure, retrofitting and post-monitoring of the growing number of old landfills reaching end-of-life (Dickinson, 1995; Reeves and Murray, 1996; 1997). At the same time, other benefits such as revenue from recovered materials and reclaimed land potentially could be obtained. In Europe and Asia, the situation was somewhat similar although in these regions the growing need for remediation of old landfills

and removal of deposits hampering urban development seems to have been important drivers for the increased interest in landfill mining as well (Cossu et al., 1996; Hogland et al., 1996; Hylands, 1998).

Around 2000, the research intensity on landfill mining suddenly decreased and since then only sporadic initiatives have been reported in the scientific literature. There could certainly be several reasons for this change in activity such as economic downturns or less demand for landfill space in certain regions of the world due to introduction of more sophisticated waste treatment and recycling programs. However, one important reason is probably the fact that many feasibility studies from the 1990s found that it often was difficult to obtain high-quality, marketable recyclables from the deposits (e.g. Savage et al., 1993; Krogmann and Qu, 1997). This is critical as it decreases the capacity for creating new landfill space or reducing the need for remediation and final closure. A “new” waste disposal problem might be generated, as well as limiting possible benefits in terms of revenue from recovered materials. Hull et al. (2005) argues that landfill mining is only economically viable under certain conditions: as an alternative option for remediation preferably co-financed from clean-up funds; for removal of deposits hampering urban development; for extraction of supplementary waste fuel in order to secure full working load at waste incinerators; or for creating new landfill space by using existing sites and infrastructure, thereby also facilitating the permitting process.

3 State-of-the-art research and knowledge

More than 90% of the reviewed papers are either conceptual discussions on landfill mining or more commonly pilot-scale investigations exploring the feasibility of mining specific deposits. Although a few success stories from the 1990s are frequently referred to in the literature (e.g. in Dickinson, 1995), more detailed descriptions of such projects that have been realized on a large scale are rare.

Characterization of deposited material is the most studied main topic within landfill mining research (e.g. Cossu et al., 1995; Hogland et al., 1995; Godio et al., 1999; Bernstone et al., 2000; Kurian et al., 2007). In fact, almost 50% of the reviewed papers involve such pilot-scale investigations, in which waste from landfills of different age and from different regions has been excavated and analysed in terms of its material composition and/or physical and chemical characteristics, Figure 2. This research has provided essential knowledge for evaluating the feasibility of mining landfills, often demonstrating variations in waste composition between different landfills and even within specific sites (Hogland, 2002; Kurian

et al., 2003; Hull et al., 2005). Such a condition adds uncertainty to the conceivability of landfill mining and indicates that site-specific investigations always are a necessity. There are, however, also some recurring patterns regarding the composition of waste deposits in the literature. Typically, municipal landfills consist of about 50-60 weight percent of a soil-type material (cover material and heavily degraded waste), 20-30 weight percent combustibles (e.g. plastic, paper and wood), 10 weight percent inorganic materials (e.g. concrete, stones and glass) and a few weight percent of metals (mainly ferrous metal). This is often the case even when considering landfills situated in totally different parts of the world (cf. Cossu et al., 1995; Krogmann and Qu, 1997; Prechthai et al., 2008). Several studies therefore also stress the potential of resource recovery, both in terms of recycling of cover soil, earth construction materials and metals, and energy recovery of combustibles (Cobb and Ruckstuhl, 1988; Obermeier et al., 1997; Hogland et al., 2004; Kurian et al., 2007). The presence of hazardous waste in the deposits has generally been found to be low, often comprising far less than one weight percent.

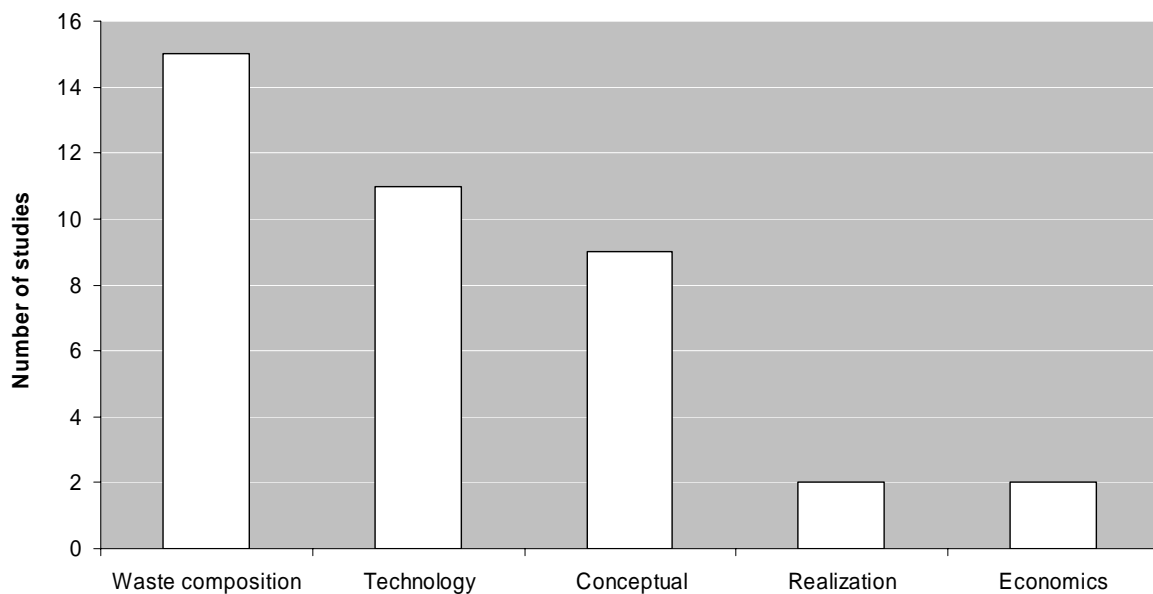


Figure 2. Categorization of the 39 reviewed papers regarding which main topic they address. For simplicity, only one main topic has been attributed to each of the papers although they also often touch upon other sub-topics. This is further described in the text.

Most of the waste composition studies also address environmental and safety issues although primarily as a sub-topic. Emphasis has been on local risks related to the excavation of landfills, i.e. leaching of hazardous substances, slope stability issues and risks for formation of explosive and poisonous gases (Hogland, 1995; Cossu et al., 1995; Zhao et al., 1997; Prechthai et al., 2008). Most of the studies conclude that the risks for occupational

health impacts are generally low, although on some occasions the generation of, for instance, landfill gas was temporarily found to be significant, especially at the bottom layers of the landfill. As a consequence, it is anticipated that authorities will in most cases plausibly require an approved safety and health plan involving procedures for management of hazardous waste, systematic monitoring of air quality, trained and well-equipped workers and so on (Cossu et al., 1996). Knowledge about exactly what administrative, regulatory and safety demands that such initiatives will involve and how in the end they will influence feasibility is however still lacking.

The second most commonly addressed main topic is technology for excavation and materials processing (e.g. Cobb and Ruckstuhl, 1988; Rettenberger, 1995; Reith and King, 1997; Cha et al., 1997; Hino et al., 1998; Chang and Kramer, 2003). This is because beneficial implementation of landfill mining virtually always relies on the fact that a large share of the excavated waste can be separated out and then recovered in some way, preferably off-site (cf. Fisher and Findlay, 1995). So far, however, emphasis has been on separating the soil-type material from the waste by using mobile screening equipment, sometimes also including an air knife and a magnet (Stessel and Murphy, 1991; Savage et al., 1993; Krogmann and Qu, 1997; Hogland, 2002). The reason for this approach is the anticipation that soil, in contrast to waste, will be fairly easily recovered. Several studies, including a few large-scale projects, have also demonstrated that a large share of the soil-type material, often containing low contamination levels, can be recovered as landfill cover material or for offsite use as filler material (Dickinson, 1995; Reeves and Murray, 1997; Kurian et al., 2003; Zhao et al., 2007). Such mobile technologies have however generally been far less efficient for obtaining other recyclables of a marketable quality, although there are a few cases in which recovery of ferrous metals and waste fuel also have been reported (e.g. EPA, 1997; Krogmann and Qu, 1997).

Another frequently occurring main topic involves theoretical discussions about possible benefits of landfill mining (e.g. Savage, 1993; Reith and Salerni, 1997; Murphy, 2000). In fact, virtually all of the reviewed papers touch upon this issue, although often briefly. According to Van der Zee et al. (2004), for instance, landfill mining *"is a process of excavating a landfill using conventional surface mining technology to recover e.g. metals, glass, plastics, soils and the land resource itself"*. This is however not a typical definition of landfill mining. In most of the research, a much broader and partially different view on this strategy is applied. A typical example of a frequently recurring definition in the literature is given by Cossu et al.

(1996) in which landfill mining is 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”*. Here, much more emphasis is placed on landfill mining as a way to solve traditional management issues related to waste deposits, while resource recovery of deposited material is simply outlined as one possible benefit among others (see also e.g. Spencer, 1990; Dickinson, 1995; Cha et al., 1997; Krogmann and Qu, 1997; Prechthai et al., 2008). So, although virtually all initiatives on landfill mining have involved some efforts to recover deposited resources, i.e. primarily cover soil material, such constituents have so far been largely subordinated to other objectives. There are however a few exceptions in terms of projects that primarily explore possibilities for recovery of specifically valuable materials from waste deposits such as metals (Hino et al., 1998), foundry sand (Zanetti and Godio, 2006) and waste fuel for energy generation (Rettenberger, 1995; Obermeier et al., 1997).

Only two papers deal with the realization process of landfill mining as a main topic. One of them discusses selected technical, economic and political factors that could influence the choice between using traditional closure of landfills or landfill mining (Bryden, 2000). The other briefly describes a general framework outlining five steps that have to be taken in order to realize landfill mining projects in the U.S.: (1) Conduct a site characterization study; (2) Assess potential economic benefits; (3) Investigate regulatory requirements; (4) Establish a preliminary worker health and safety plan; and (5) Assess project costs (EPA, 1997). A reason for this lack of interest in how to actually proceed in order to realize such projects is presumably that most of the initiatives have so far been fully occupied by addressing the initial step of such a process, i.e. site-specific characterization studies.

Even though almost 40% of the reviewed papers touch upon economic aspects (e.g. Savage et al., 1993; Rettenberger, 1995; Krogmann and Qu, 1997); there are only two studies that strictly focus on this issue as their main topic (Fisher and Findlay, 1995; Van der Zee et al., 2004). In both these papers, possible costs and benefits that may or may not appear in such projects are outlined on a general level. Some of the listed benefits are reduced costs due to more efficient operation of landfills (e.g. increased disposal capacity or avoidance of remediation efforts) or revenue from recycled materials and reclaimed land. Possible costs could be divided into capital costs (e.g. site preparation, developing consents and purchase

of technologies for excavation and processing) and operational costs (e.g. labor, fuel, waste disposal fees, regulatory compliance expenses and hauling costs). The economic feasibility of landfill mining has however not yet been thoroughly addressed – in some cases such initiatives have been considered beneficial while in others they have not (e.g. Cobb and Ruckstuhl, 1988; Savage et al., 1993; Cossu et al., 1996; Bryden, 2000). Within the literature, there is more or less a consensus that every landfill mining project has its unique set of conditions and objectives which either directly or indirectly influence its economic feasibility.

4 Challenges for the future

4.1 Landfill mining in the past

Developing a common understanding of the meaning of a concept or strategy is fundamental since it influences how such initiatives will be planned and realized and within what context they will finally be evaluated. The tentative definition of landfill mining derived from the Oxford Dictionary of English at the beginning of this article solely emphasizes resource recovery from landfills. This definition does not however accurately describe how this strategy so far has been applied in practice. In the reviewed papers, the three most commonly stated main objectives for landfill mining projects have been extension of landfill life time, consolidation of landfill area facilitating final closure and remediation (e.g. Spencer, 1990; Dickinson, 1995; Cha et al., 1997; Krogmann and Qu, 1997; Prechthai et al., 2008). The employed technology has therefore typically involved simple excavation and screening equipment, often making it possible to extract and recover a large share of the soil-type material and thereby contributing to the core objectives above (Fisher and Findlay, 1995). As mentioned previously, however, such technologies have often proved moderate in obtaining marketable recyclables from the deposited waste.

The research on landfill mining has thus so far strongly been conducted within the waste management community, in which a traditional research topic has been to analyze ways for obtaining a more efficient operation of waste deposits. This view on landfill mining as a strategy for solving traditional waste management issues has of course also influenced how such initiatives have been evaluated. Generally, the economic feasibility of landfill mining has been considered in relation to alternative costs for, e.g., traditional closure and post management, remediation or re-siting a new landfill (Spencer, 1990; Fisher and Findlay, 1995; Dickinson, 1995; Murphy, 2000). In the U.S, for instance, several initiatives during the 1990s were reported to be economically justified solely by extending the service life of the landfills. However, despite strong optimism about the potential of landfill mining in the

literature, the lack of reported large-scale projects indicates that within such a waste management context this strategy has in many cases not yet been an economic option (cf. Bryden, 2000; Hull et al., 2005).

4.2 Landfill mining as a resource extraction strategy

At present, there are several worldwide changes underway that are likely to make resource extraction from alternative sources a more and more viable option such as rapidly growing competition for resources, increasing raw material prices, the large-scale environmental problems we now face and the fact that the natural reservoirs for many valuable resources are rapidly declining (Kapur, 2006; Halada, 2009). At the same time, several studies belonging to the research field of Industrial ecology show that in many regions of the world massive amounts of metals have accumulated in landfills (Lifset et al., 2002; Kapur and Graedel, 2006; Müller et al., 2006). On a global level, for instance, the amount of copper situated in such deposits (i.e. 393 million tonnes) has been estimated as comparable in size to the present stock in use within the technosphere (i.e. 330 million tonnes). Ongoing research in Sweden also indicates that apart from metals, the amount of potential waste fuel situated in municipal landfills is enough to cover the district heating demand in the country for 10 years (Krook et al., manuscript). Such findings challenge the current view on landfills as final storage locations for waste and indicate the emergence of a new perspective on landfill mining, primarily as a strategy for extracting valuable material and energy resources.

Although the potential of resource recovery from landfills appears huge, facilitating the realization of such a new perspective on landfill mining also involves a number of challenges. For any emerging strategy, the issue of uncertainty is often an overall factor prohibiting implementation since it makes it difficult for companies to foresee the outcome of such initiatives. One such critical uncertainty related to resource recovery from landfills is of course the performance of *technology*, i.e. which materials can actually be separated out from deposited waste and, perhaps even more important, at what quality levels? There are a few pilot-scale studies that have demonstrated that it already is technically possible to extract high-quality metals (both ferrous and non-ferrous) and waste fuel from landfills if more sophisticated semi-mobile or stationary processing plants are applied (Rettenberger, 1995; Obermeier et al., 1997; Hino et al., 1998; Zanetti and Godio, 2006). Much more research on available technologies and their efficiency, capacity and suitability for landfill mining is needed however. In some projects, it might only be justified to use mobile equipment whereas in others more advanced stationary processing plants could be an

option. One thing however is for certain. If the core objective is resource extraction, the conventional surface mining technologies that have been used in the past will not be sufficient.

In order to realize any project of considerable size, it is becoming increasingly important to demonstrate its *environmental performance*. As been described in this study, however, landfill mining research has so far exclusively dealt with local risks. Although this has been a useful and necessary approach, it is also insufficient because resource recovery from landfills will presumably also generate environmental consequences on regional and global scales. According to Cohen-Rosenthal (2004), for instance, “a 50 acre landfill might contain as much as 240,000 tons of steel and 20,000 tons of aluminum”. Recycling such amounts of metal, and thereby replacing virgin production, will lead to large energy savings and avoidance of all sorts of environmental pollution (Ayres, 1997). Furthermore, the amount of combustibles in landfills that potentially could be used for energy recovery is typically several orders of magnitude larger. At the same time, the extraction, processing, transportation and recycling of deposited materials will require both material and energy resources. So, in order to address the environmental performance of this new perspective on landfill mining, there is a need for a systems approach addressing the positive and negative impacts taking place on the local, regional and global scales (cf. Udo de Haes et al., 2000; Finnveden and Moberg, 2005).

In order for landfill mining to be feasible for individual companies, economic benefits must of course outweigh the costs. So far, this type of project has mainly been initiated, funded and operated by local authorities, i.e. owners of landfills, aiming to solve a specific issue of relevance for their region such as lack of landfill space (Dickinson, 1995; Van der Zee et al., 2004). Initiatives emphasizing extraction of valuable resources from deposits on commercial grounds are however something significantly different. First of all, such projects should at least not solely be evaluated from a waste management perspective but also within a broader resource management context, where the feasibility is compared to alternative costs for extracting the resources from their natural reservoirs. Furthermore, it is not likely that landfill owners on their own are in the position of meeting the technical, economic, environmental, legislative and other institutional conditions that will follow such activities. Binding different types of expert knowledge to the projects by developing a closer collaboration with actors belonging to different lines of business might therefore be necessary, e.g. material companies, energy producers, metals recyclers and so on. Such

partnerships could also have direct economic consequences. In Sweden, for instance, it is prohibited to landfill combustible materials, and waste incinerators often have a monopoly status on the local market. Waste producers therefore do not have many alternatives other than to deliver their waste to the local incinerator at a cost which varies from 53 to 106 € per tonne (The Swedish Waste Association, 2007). For a landfill owner practicing landfill mining, such a fee may be detrimental due to the generally large amount of combustibles situated in waste deposits, while the revenues for the produced heat and electricity go exclusively to the incinerators. This implies that either actors that own incinerators should perform resource recovery from landfills, or else a close collaboration between owners of landfills and incinerators has to be developed, possibly involving the splitting of costs and benefits. Such business agreements could in fact be interesting also for incinerators in order to secure a full working load of their plants in the years to come. Waste incinerators in Sweden, as well as in Germany and the Netherlands, have now experienced overcapacity for the first time ever, and this trend is also expected to continue (e.g. Profu, 2010).

Landfills as future resource reservoirs also call for a more proactive approach in terms of prospecting for the most profitable landfills to mine. In many countries, there are thousands of landfills (cf. SEPA, 1986; Van der Zee et al., 2004), which vary in regards to ownership, location, composition and age – site-specific factors, any of which might influence the profitability of mining. Some of them might contain large amounts of valuable materials such as metals and almost no hazardous waste and be located close to waste treatment and recycling plants, while for others the conditions may not be as favorable. In this respect, it could be useful to learn from how such implications have been dealt with in other lines of business such as within the mining industry. However, in order to develop such prospecting tools, knowledge about the critical factors for profitable mining of landfills must first be developed. As been pointed out previously, there are many possible benefits and costs that may or may not occur in such projects dependent on e.g. objectives, applied technologies, regulatory requirements, actors' constellations and site-specific factors of the landfill in question. So, developing such different concepts for realizing resource recovery from landfills and then evaluating their environmental and economic performance sums up some of the key future research challenges for facilitating implementation.

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