New Concept and Methods to Evaluate the Sustainability of Landfills

Marion Huber-Humer, Ena Smidt, Johannes Tintner, Oliver Gamperling, Katharina Böhm, Peter Lechner

Institute of Waste Management
BOKU - University of Natural Resources and Applied Life Sciences
Vienna, Austria

CONTACT
Marion Huber-Humer
Institute of Waste Management
BOKU - University of Natural Resources and Applied Life Sciences Vienna
Muthgasse 107/3rd floor
1190 Vienna, Austria

++43 1 318 99 00
++43 1 318 99 00 – 350

marion.huber-humer@boku.ac.at

EXECUTIVE SUMMARY

“Sustainable landfilling” is a key-issue in many modern waste management concepts. However, we still have to take care about our old landfills and we have to evaluate and monitor the environmental impact of our modern sites. No internationally accepted definition of a “sustainable landfill” has been identified to date. In this paper a sustainable landfill is understood as a landfill where the disposed off waste mass is already in a stable state, meaning the remaining turnover processes are low and emission release is below the local environmentally acceptable level or can be controlled by simple, robust and natural measures, e.g. methane oxidation in landfill covers. Moreover, most of the remaining carbon (and nitrogen) is bounded in stable substances and the landfill can be regarded as a long-term carbon storage pool. In order to evaluate, assess and quantify these processes and pools new methodologies and analytical tools are needed. Modern analytical methods adapted for purposes in waste management and monitoring, like the thermal behaviour, spectral features and the bioavailability of waste samples supported by multivariate statistical methods are the basis of a new innovative concept, which is currently under development at the ABF-BOKU. First results, the applicability of these methods and the idea of this evaluation concept to assess the sustainability of landfills is briefly presented and referenced in this paper.
INTRODUCTION

“Sustainable landfilling” is a key-issue in many modern waste management concepts. We have indeed learned our lessons from past landfill practice, although are still facing today numerous problems associated with long lasting gas and leachate emissions and costly aftercare procedures. We are now looking towards the future in the hope of establishing new landfill concepts that no longer pose a risk to human health, the environment and global climate. However, we still have to take care about our old landfills and we have to evaluate and monitor the environmental impact of our modern sites. Moreover, no internationally accepted definition of “sustainable landfilling” has been identified to date. With respect to landfills very often terms including stability, completion, end-point and no-threat to the environment are used in discussions on sustainability. Currently, there are international working groups active in addressing and discussing this issue (e.g. IWWG Task group “Sustainable Landfilling”, http://iwwg.eu/task-groups/sustainable-landfilling).

The implementation of corresponding legislation and economic tools such as the account in diverse carbon credit schemes (e.g., CDM) is paralleled by the development of adequate analytical tools in order to verify the compliance with the required standards and to assess the effect of final carbon and nitrogen sinks. Therefore new methodologies and analytical tools are needed in the future. Innovative methods and indicators are under development at the Institute of Waste Management (ABF-BOKU), which shall be merged in a comprehensive concept that allow a quick assessment of landfilled waste materials (old landfills, bioreactor landfills, landfilled mechanically biologically pretreated material, inorganic residues). Modern analytical methods adapted for purposes in waste management and monitoring, like the thermal behaviour, spectral features and the bioavailability of waste samples supported by multivariate statistical methods are the basis of this innovative concept. First results, the applicability of these methods and concept are presented and discussed in this paper.

SUSTAINABLE LANDFILL CONCEPT

Sustainability of anthropogenic activities requires a clear definition of this term in a specific area and the implementation of adequate criteria to reach the goal. New strategies in waste management focus on stabilization and safe final disposal of waste materials that cannot be integrated in a closed loop in the short term. Sustainability in the context of landfilling means a multi-barrier concept that includes the appropriate geological background, the technical landfill equipment and mechanical-biological or thermal treatment of waste prior to landfilling.

No internationally accepted definition of “sustainable landfilling” has been identified to date. With respect to landfills very often terms including stability, completion, end-point and threat to the environment are used in discussions on sustainability (Scharff et al., 2007). Cossu (2007) defines a sustainable landfill as a system that should reach an acceptable equilibrium with the environment within one generation (30-40 years). When physical barriers fail due to aging (the life span of geomembranes and traditional mineral liners does not exceed one generation; Cossu, 2005 cited in Cossu, 2007) emission release should be below the environmentally acceptable level in order to avoid a threat to human health and the environment. This is particularly crucial when considering the standard use in Europe of insulating landfills by means of impermeable liners (Scharff et al., 2007). Insulation interrupts all landfill processes, but liners - as mentioned above - will only hold...
over a limited period and will inevitably fail at some (unknown) point in future. When the liners fail, the processes as driving force for emission will start up again.

In this paper a “sustainable” landfill is understood as a landfill where the disposed off waste mass is already in a stable state, meaning the remaining turnover processes are low and emission release is below the local environmentally acceptable level or can be controlled by simple, robust and natural measures, e.g. control of gas emissions by methane oxidation in landfill covers. Moreover, most of the remaining carbon (and nitrogen) is bounded in stable substances and the landfill can be regarded as a long-term carbon storage pool. The control and mitigation of greenhouse active gas emissions from landfills and the enhancement and evaluation of the carbon and nitrogen storage pool are main issues nowadays and will be in the future.

The way how to put the principle of sustainable landfilling into practice represents one of the main research issues for the scientific community in the field (Cossu, 2007). Several promising pre-treatment, in situ treatment, and post-treatment measures and technologies have already been presented or are currently undergoing development to achieve a sustainable landfill concept with acceptable aftercare phases of about one generation. The latter aim is most likely achievable for modern landfills already receiving pre-treated and separated waste streams (waste quality = “internal barrier”). Moreover, promising technologies, such as in-situ aeration or flushing technologies, to enhance landfill processes and shorten aftercare periods of old, closed municipal solid waste landfills containing untreated wastes with high amount of degradable fractions and consequently high emission potential are currently available.

With respect to landfill sustainability, particularly greenhouse active landfill gas emissions should be avoided to a large extent. For controlling and mitigating remaining methane emissions robust biocover systems can be applied. By providing optimum conditions for microbial methane oxidation and efficiently routing landfill gas to where these processes are enhanced, a number of bio-based systems, like interim or long-term biocovers, passively or actively vented biofilters, biowindows and daily-used biotarps, have been developed (Huber-Humer et al. 2008). These bio-based systems have a wide range of applications. They can be used with gas collection to capture fugitive emissions; or alone during new landfill start-up; at older landfills past peak production; at small sites where gas collection is not technically and economically feasible; at closed landfills to polish fugitive methane emitted when during post-closure forced in-situ aeration is used to reduce waste reactivity and aftercare duration time; and in instances where the landfilled wastes have a low lifetime gas generation potential, so that gas collection is infeasible. An example of the latter are landfills containing mechanically and biologically pretreated (MBT) wastes (Huber-Humer et al., 2008).

**TOOLS FOR EVALUATION**

In the following sections some innovative approaches are shortly summarized and referenced that shall help to evaluate and assess the sustainability of a landfill. Main focus in this paper is on landfills that received a high content of biodegradable organic matter in the past (“classic” municipal solid waste landfill, old dumps), or where mechanically-biologically pre-treated waste is disposed off now, respectively. However, the evaluation tools for the solid waste mass are also applicable to MSWI bottom ashes.
Innovative Monitoring Tools to Evaluate the Solid Waste Mass

During the last decade analytical tools such as Fourier transform infrared (FTIR) spectroscopy and thermal analysis have gained in importance in the field of waste analytics. These methods are used in many industrial areas for process and quality control and have proven to be appropriate tools for waste characterization. FT-IR spectra reveal the chemical composition of the material due to interactions of functional groups with infrared radiation. The thermal behavior depends on physical parameters and the chemical composition of the waste material. Both methods characterize the whole sample by many data points and therefore provide comprehensive information on the material, its composition, its properties, and its behavior. The stage of degradation and the related reactivity/stability of waste organic matter are in the focus of interest. In association with multivariate statistical methods waste classification and parameter prediction can be carried out. Depending on the questions to be answered corresponding models are developed (Meissl et al. 2007, Smidt et al. 2008, Smidt et al. 2009). This is a prerequisite for practical application as they perform the transformation of the complex spectral or thermal pattern into readily comprehensible information or a single value. Figs. 1 (a) and (b) display the development of municipal solid waste by means of spectral and thermal characteristics. Changes in the chemical composition are evident. The intensity of bands that are assigned to organic functional groups decreases with progressing mineralization (2920 and 2850 cm\(^{-1}\), 1740 cm\(^{-1}\), 1540 cm\(^{-1}\), 1320 cm\(^{-1}\) and 1260 cm\(^{-1}\)). Bands of inorganic functional groups dominate the spectrum in stabilized landfilled materials (carbonates at 1420 and 875 cm\(^{-1}\) and clay minerals at 1030 cm\(^{-1}\)). Changes in the chemical composition are also reflected by the thermal behavior. Degradation of waste organic matter causes heat flow curves to decrease. It is paralleled by decreasing enthalpies of waste dry matter. By contrast, the enthalpy of the remaining recalcitrant organic matter increases which might be an adequate indicator for stability.
Besides degradation of organic matter by microbial activity, inorganic residues from municipal solid waste incineration (bottom ash) undergo a chemical process of stabilization by CO2 uptake (carbonation) that can be revealed by these methods. Fig. 2 visualizes the process of carbonation by changes of the infrared spectral and thermal pattern. The increase of relevant “carbonate” bands at 1420 and 875 cm⁻¹ in the spectrum (a) and the higher mass loss > 650 °C (b) by carbonate decay (thermogravimetry) due to progressing carbonation of MSWI bottom ash become visible.

Fig. 2: Carbonation of MSW incinerator bottom ash: (a) spectral and (b) thermal characteristics before (a) and after (b) additional CO2 uptake.

Monitoring and assessment of abandoned and operating landfills regarding their stability as well as process control and compliance with limit values in terms of reactivity are main fields of application. Fig. 3a shows the correlation between measured and predicted gas generation sum (GS21) of mechanically-biologically treated (MBT) municipal solid waste,
based on infrared spectral data and partial least squares regression (PLS-R). Fig. 3b displays the correlation between measured (references) and predicted calorific values of MBT-material based on the heat flow profile and PLS-R (Böhm et al. 2010, Smidt et al. 2010). Especially for time-consuming and error-prone parameters the development of prediction models provides several advantages such as fast and easy handling, avoidance of chemical analyses and minimization of failures.

**Fig. 3:** Correlation between (a) the gas generation sum (GS21) and infrared spectral data and between (b) the calorific value and heat flow profiles based on partial least squares regression

**Innovative Monitoring Tool for Leachate Characterisation**

Apart from solid waste characterisation, particular attention should be paid to leachate quality and its changes, primarily focusing on nitrogen compounds, which significantly influence the duration of the aftercare-phase and the required effort for leachate treatment. In contrast to solid waste samples taken from the landfill body, which represent often only a snapshot in spatial distribution and sample taking is quite difficult, costly and time-consuming, leachate represents a sum-parameter reflecting the status quo of an entire landfill, or landfill section, respectively.

Investigation of landfill leachate using innovative methods such as FTIR (see above) provides an additional comprehensive approach to assess the sustainability of a landfill. Huo et al. (2008) used FT-IR spectroscopy to detect magnesium, ammonium and phosphate in landfill leachate. Zhang et al. (2008) applied FT-IR spectroscopy to verify the removal of dissolved organic matter from landfill leachate by nanofiltration. Pelaez et al. (2009) investigated leachate from a municipal solid waste landfill using FT-IR spectroscopy.

At the ABF-BOKU (Gamperling et al., 2009) FT-IR spectroscopy was applied to characterise leachate from aerated as well as anaerobically treated waste material and conventional parameters such as ammonium nitrogen (NH4-N), and chemical oxygen demand (COD) were determined by this method. Sample preparation for spectroscopic investigations includes freeze-drying of leachate samples and milling with pestle and
mortar. Partial least squares regression (PLS-R) was applied showing correlation between spectral characteristics and NH4-N contents, and COD concentrations, respectively. The correlation coefficient for NH4-N was 0.75 (mean error of 88 mg l-1, 51 data points); for the COD correlation 61 samples were available resulting in a correlation coefficient of 0.92 (mean error 666 mg O2 l-1). The results obtained by Gamperling et al., (2009) illustrate that a prediction of these leachate parameters by infrared spectroscopy is feasible.

Various metabolic processes towards mineralisation occur in the solid waste material in landfills, which are reflected by changes in the chemical composition of the solid waste, and consequently by alteration of leachate characteristics. The latter can be observed by FT-IR spectroscopy at a molecular level. During the anaerobic phase the leachate is mainly characterised by a high ammonium-nitrogen concentration (NH4-N). Ammonium is reflected by the FT-IR spectra at wavenumbers 700 cm\(^{-1}\), 820 cm\(^{-1}\) and 1550 cm\(^{-1}\). Leachate from anaerobically treated waste is dominated by the bands at wavenumbers 2920 and 2850 cm\(^{-1}\), 2550-2530 cm\(^{-1}\), 1560 cm\(^{-1}\), 1390 cm\(^{-1}\), 835 cm\(^{-1}\), 740 cm\(^{-1}\) and 700 cm\(^{-1}\), which can be assigned to functional groups of biodegradable organic compounds. Decomposition of easily biodegradable substances (e.g. mercaptan at 2530-2550 cm\(^{-1}\)) results in an evident decrease of the band that is assigned to the S-H vibration (Gamperling et al., 2009).

**Monitoring of Landfill Cover, Gas Emissions and Methane Oxidation on Landfills**

As a first approach of landfill exploration vegetation ecology can give quick and comparatively cheap information. The base of this method is the fact that plant species differ in their claim for water, nutrients and in their response on stresses like higher salinity or oxygen limitations. These effects cause a physiological amplitude for each species. In a real habitat the concurrence of different species leads to a distortion of this amplitude towards the ecological amplitude. These amplitudes were observed by Ellenberg for all plant species in middle Europe (Ellenberg et al., 1992).

Due to its composition and structure the landfill surface differs from the natural environment. Exploration of the landfill is based on bio-indication. Plants expose and visualize many factors and conditions over a longer period of time and shed light on the habitat’s features by particular species and their succession, their frequency, and diverse indicator properties. Evaluation of surface characteristics with respect to vegetation is performed by multivariate data analysis. A better insight, for instance identification of hot spots of gaseous emissions, supports the sampling design and allows remediation control. (Tintner and Klug, 2007; Tintner and Klug, in press). Vegetation and population ecology helps us

- to find out the reasons of failures in recultivation,
- to deduct information about possible emissions, but also possible plant communities on different landfill top covers,
- to distinguish parts with a different history within one landfill,
- to get insight in the quality and quantity of soil seed banks in landfill top covers, and
- to initiate a vegetation development on landfill top covers towards plant communities of higher ecological value.

In times of shrinking physical and natural resources, future landfill management should take these aspects into account (Klug et al., 2008; Tintner et al., 2008).
The quantification of landfill methane emissions and the evaluation of biobased methane oxidation systems is still a challenge today. Principally, various techniques, commonly used to monitor landfill surface emissions, can be applied to control biocovers as well. Quantification of methane oxidation and biocover efficiency in the field requires the use of sophisticated concepts and methods. Nevertheless, it is unfeasible to maintain that a single solution may represent the best practice. Indeed, it is invariably necessary to distinguish between different purposes, scales and tasks, such as control of the cover layer and performance in landfill operation, or in contrast, reporting for national gas emission inventories. For the first “local” purpose FID surface scanning combined with chamber/tunnel measurements may present a pragmatic method, whilst for the second “large scale” approaches, such as tracer techniques capable of monitoring whole site emissions, may be more practicable. Positive experiences have been obtained using an open flux-tunnel for the quantification of emissions from coarse, well-permeable compost covers (Huber-Humer et al., 2009). Alternatively, gas measurements may be combined with isotope investigations to directly assess the in-situ oxidation proportion, which is one of the most promising evaluation approaches for biocover systems today (De Visscher et al., 2004; Chanton et al., 2000). However, several limitations caused by variations in methane stable isotope ratios consequent to an extremely specific fractionation due to individual characteristics of methanotrophs and growth condition (Nozhevnikova et al., 2003), and fractionation processes during gas transport (De Visscher et al., 2004), must be still resolved prior to practical application.

CONCLUSIONS

Through newly applied pre-treatment and in-situ stabilization methods of biodegradable waste prior and during landfilling not only greenhouse gas emissions can be avoided but also a human-made terrestrial C-storage pool can be created and thereby positively impacting climate change. Providing these issues, “sustainable landfilling” can be widely achieved. However, adequate measurement and monitoring methods to evaluate and quantify these positive effects are rare so far and must be developed and implemented. Characterizing chemical and physical properties of treated MSW by means of infrared spectroscopy and simultaneous thermal analysis in association with the degradation behaviour is a promising approach to define long-term stability of landfilled waste materials. These methods have been developed for their application in waste management during the past years and are currently under further adaptation. Moreover, robust bio-based methods (biocovers, biowindows, etc.) exist to mitigate remaining methane emissions from landfills and to reduce the impact of landfills on the greenhouse effect. In order to evaluate the efficiency of such bio-systems and quantify the reduction of greenhouse gas emissions new and applicable methods are under development and need to be transferred into practical application as well.

REFERENCES


