From:	Bruce Cowger
To:	Coffin Butte Landfill Appeals
Cc:	Bruce Cowger
Subject:	Testimony regarding LU-24-027, the application to expand the landfill
Date:	Saturday, August 30, 2025 9:52:01 AM
Attachments:	Insights on volatile metals in landfill gas as determined from advanced treatment media - ScienceDirect.pdf Landfill gas as a source of anthropogenic antimony and arsenic release - ScienceDirect.pdf ATSDR - Landfill Gas Primer - Chapter 2_ Landfill Gas Basics.pdf Characterisation of VOCs emitted by open cells receiving municipal solid waste - ScienceDirect.pdf Trace gas emissions from municipal solid waste landfills_ A review - ScienceDirect.pdf

Testimony for the Benton County Board of Commissioners

From: Bruce Cowger, 37194 Helm Drive, Corvallis, OR 97330 (since 1985)

Scientists around the world have, for years, studied the emissions from municipal solid-waste (MSW) landfills. Earlier studies tend more to focus on liquid waste, or leachate, from these landfills. Recently, the gaseous emissions or landfill gas (LFG) have received widespread and detailed analysis.

Attached are summaries of five studies, none of which mention PFA (forever chemicals), the fluoro-carbon synthetic chemicals that give us stain-resistant carpets, non-stick cookware, and waterproof outdoor clothing such as Gore-Tex and other brands. I will submit separately, studies showing the alarming level of PFAs emerging from US landfills.

The present studies, based on landfills in the US, all document how various compounds are being carried out of landfills by decomposition gases. To be sure, methane and CO2 comprise some 98 - 99% of LFG and their impact on global warming is not to be underestimated. Not to be neglected, however, are the trace amounts of carcinogens, teratogens (causing birth defects) and mutagens (causing mutations) regularly found in LFG and there is every reason to believe these are currently spewing out of the Coffin Butte Landfill (CBL). After all, there is little difference between the solid-waste from western Oregon and that being compacted into other US landfills.

Are Benton County residents dropping dead from the non-methane organic compounds (NMOCs) being emitted from CBL? No. But just as smoking was thought to be healthful in the post WWII period and thalidomide was believed to be free of undesirable side effects when it was introduced in 1957, we often identify unhealthful practices only in retrospect. This is now the case before Benton County: Were an industry known to emit carcinogenic gases (e.g. methyl ethyl ketone, organic and non-organic compounds of antimony and arsenic) apply for a building permit within Benton County, they would not receive a warm welcome.

But we do, in fact, have such a business today. I strongly urge the Board of Commissioners to deny Republic's bid to expand the Coffin Butte landfill. The health impacts of the various toxins emitting from CBL may not be known for years. But when they become apparent, those impacts will fall squarely on the citizens of Benton, Polk, and Linn counties and our children and grandchildren will wonder how this landfill was allowed to operate for so long.

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Chapter 2: Landfill Gas Basics

Historical Document

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This chapter provides basic information about landfill gas—what it is composed of, how it is produced, and the conditions that affect its production. It also provides information about how landfill gas moves and travels away from the landfill site. Finally, the chapter presents an overview of the types of landfills that might be present in your community and the regulatory requirements that apply to each.

What is landfill gas composed of?

Landfill gas is composed of a mixture of hundreds of different gases. By volume, landfill gas typically contains 45% to 60% methane and 40% to 60% carbon dioxide. Landfill gas also includes small amounts of nitrogen, oxygen, ammonia, sulfides, hydrogen, carbon monoxide, and nonmethane organic compounds (NMOCs) such as trichloroethylene, benzene, and vinyl chloride. Table 2-1 (#t2_1) lists "typical" landfill gases, their percent by volume, and their characteristics.

How is landfill gas produced?

Three processes—bacterial decomposition, volatilization, and chemical reactions—form landfill gas.

- **Bacterial decomposition.** Most landfill gas is produced by bacterial decomposition, which occurs when organic waste is broken down by bacteria naturally present in the waste and in the soil used to cover the landfill. Organic wastes include food, garden waste, street sweepings, textiles, and wood and paper products. Bacteria decompose organic waste in four phases, and the composition of the gas changes during each phase. The box below (#four) provides detailed information about the four phases of bacterial decomposition and the gases produced during each phase. Figure 2-1 (#f2_1) shows gas production at each of the four stages.

- **Volatilization**. Landfill gases can be created when certain wastes, particularly organic compounds, change from a liquid or a solid into a vapor. This process is known as volatilization. NMOCs in landfill gas may be the result of volatilization of certain chemicals disposed of in the landfill.

- **Chemical reactions.** Landfill gas, including NMOCs, can be created by the reactions of certain chemicals present in waste. For example, if chlorine bleach and ammonia come in contact with each other within the landfill, a harmful gas is produced.

Table 2-1: Typical Landfill Gas Components

Component	Percent by Volume	Characteristics
methane	45–60	Methane is a naturally occurring gas. It is colorless andodorless. Landfills are the single largest source of U.S. man-made methane emissions
carbon dioxide	40–60	Carbon dioxide is naturally found at small concentrations in the atmosphere (0.03%). It is colorless, odorless, and slightly acidic.

nitrogen	2–5	Nitrogen comprises approximately 79% of the atmosphere. It is odorless, tasteless, and colorless.
oxygen	0.1–1	Oxygen comprises approximately 21% of the atmosphere. It is odorless, tasteless, and colorless.
ammonia	0.1–1	Ammonia is a colorless gas with a pungent odor.
NMOCs (non-methane organic compounds)	0.01–0.6	NMOCs are organic compounds (i.e., compounds that contain carbon). (Methane is an organic compound but is not considered an NMOC.) NMOCs may occur naturally or be formed by synthetic chemical processes. NMOCs most commonly found in landfills include acrylonitrile, benzene, 1,1-dichloroethane, 1,2-cis dichloroethylene, dichloromethane, carbonyl sulfide, ethyl-benzene, hexane, methyl ethyl ketone, tetrachloroethylene, toluene, trichloroethylene, vinyl chloride, and xylenes.
sulfides	0–1	Sulfides (e.g., hydrogen sulfide, dimethyl sulfide, mercaptans) are naturally occurring gases that give the landfill gas mixture its rotten-egg smell. Sulfides can cause unpleasant odors even at very low concentrations.
hydrogen	0–0.2	Hydrogen is an odorless, colorless gas.
carbon monoxide	0–0.2	Carbon monoxide is an odorless, colorless gas.

Source: Tchobanoglous, Theisen, and Vigil 1993; EPA 1995

The Four Phases of Bacterial Decomposition of Landfill Waste

Bacteria decompose landfill waste in four phases. The composition of the gas produced changes with each of the four phases of decomposition. Landfills often accept waste over a 20- to 30-year period, so waste in a landfill may be undergoing several phases of decomposition at once. This means that older waste in one area might be in a different phase of decomposition than more recently buried waste in another area.

Phase I

During the first phase of decomposition, aerobic bacteria—bacteria that live only in the presence of oxygen—consume oxygen while breaking down the long molecular chains of complex carbohydrates, proteins, and lipids that comprise organic waste. The primary byproduct of this process is carbon dioxide. Nitrogen content is high at the beginning of this phase, but declines as the landfill moves through the four phases. Phase I continues until available oxygen is depleted. Phase I decomposition can last for days or months, depending on how much oxygen is present when the waste is disposed of in the landfill. Oxygen levels will vary according to factors such as how loose or compressed the waste was when it was buried.

Phase II

Phase II decomposition starts after the oxygen in the landfill has been used up. Using an anaerobic process (a process that does not require oxygen), bacteria convert compounds created by aerobic bacteria into acetic, lactic, and formic acids and alcohols such as methanol and ethanol. The landfill becomes highly acidic. As the acids mix with the moisture present in the land-fill, they cause certain nutrients to dissolve, making nitrogen and phosphorus available to the increasingly diverse species of bacteria in the landfill. The gaseous byproducts of these processes are carbon dioxide and hydrogen. If

the landfill is disturbed or if oxygen is somehow introduced into the landfill, microbial processes will return to Phase I.

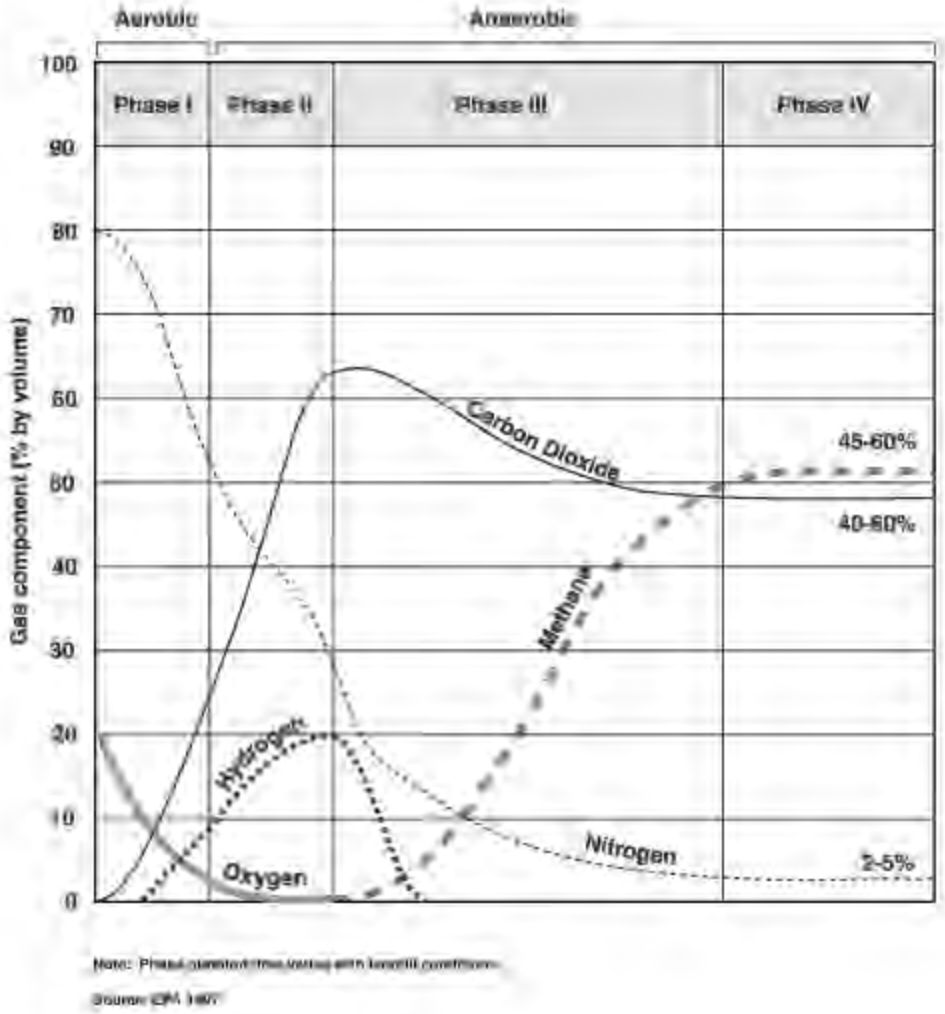
Phase III

Phase III decomposition starts when certain kinds of anaerobic bacteria consume the organic acids produced in Phase II and form acetate, an organic acid. This process causes the landfill to become a more neutral environment in which methane-producing bacteria begin to establish themselves. Methane-and acid-producing bacteria have a symbiotic, or mutually beneficial, relationship. Acid-producing bacteria create compounds for the methanogenic bacteria to consume. Methanogenic bacteria consume the carbon dioxide and acetate, too much of which would be toxic to the acid-producing bacteria.

Phase IV

Phase IV decomposition begins when both the composition and production rates of landfill gas remain relatively constant. Phase IV landfill gas usually contains approximately 45% to 60% methane by volume, 40% to 60% carbon dioxide, and 2% to 9% other gases, such as sulfides. Gas is produced at a stable rate in Phase IV, typically for about 20 years; however, gas will continue to be emitted for 50 or more years after the waste is placed in the landfill (Crawford and Smith 1985). Gas production might last longer, for example, if greater amounts of organics are present in the waste, such as at a landfill receiving higher than average amounts of domestic animal waste.

Figure 2-1: Production phases of typical landfill gas



What conditions affect landfill gas production?

The rate and volume of landfill gas produced at a specific site depend on the characteristics of the waste (e.g., composition and age of the refuse) and a number of environmental factors (e.g., the presence of oxygen in the landfill, moisture content, and temperature).

- **Waste composition.** The more organic waste present in a landfill, the more landfill gas (e.g., carbon dioxide, methane, nitrogen, and hydrogen sulfide) is produced by the bacteria during decomposition. The more chemicals disposed of in the landfill, the more likely NMOCs and other gases will be produced either through volatilization or chemical reactions.
- **Age of refuse**. Generally, more recently buried waste (i.e., waste buried less than 10 years) produces more landfill gas through bacterial decomposition, volatilization, and chemical reactions than does older waste (buried more than 10 years). Peak gas production usually occurs from 5 to 7 years after the waste is buried.
- **Presence of oxygen in the landfill.** Methane will be produced only when oxygen is no longer present in the landfill.
- **Moisture content.** The presence of moisture (unsaturated conditions) in a landfill increases gas production because it encourages bacterial decomposition. Moisture may also promote chemical reactions that produce gases.
- **Temperature.** As the landfill's temperature rises, bacterial activity increases, resulting in increased gas production. Increased temperature may also increase rates of volatilization and chemical reactions. The box on the following page provides more detailed information about how these variables affect the rate and volume of landfill gas production.

How does landfill gas move?

Once gases are produced under the landfill surface, they generally move away from the landfill. Gases tend to expand and fill the available space, so that they move, or "migrate," through the limited pore spaces within the refuse and soils covering of the landfill. The natural tendency of landfill gases that are lighter than air, such as methane, is to move upward, usually through the landfill surface. Upward movement of landfill gas can be inhibited by densely compacted waste or landfill cover material (e.g., by daily soil cover and caps). When upward movement is inhibited, the gas tends to migrate horizontally to other areas within the landfill or to areas outside the landfill, where it can resume its upward path. Basically, the gases follow the path of least resistance. Some gases, such as carbon dioxide, are denser than air and will collect in subsurface areas, such as utility corridors. Three main factors influence the migration of landfill gases: diffusion (concentration), pressure, and permeability

- **Diffusion (concentration).** Diffusion describes a gas's natural tendency to reach a uni-form concentration in a given space, whether it is a room or the earth's atmosphere. Gases in a landfill move from areas of high gas concentrations to areas with lower gas concentrations. Because gas concentrations are generally higher in the landfill than in the surrounding areas, landfill gases diffuse out of the landfill to the surrounding areas with lower gas concentrations.

- **Pressure.** Gases accumulating in a landfill create areas of high pressure in which gas movement is restricted by compacted refuse or soil covers and areas of low pressure in which gas movement is unrestricted. The variation in pressure throughout the landfill results in gases moving from areas of high pressure to areas of low pressure. Movement of gases from areas of high pressure to areas of lower pressure is known as convection. As more gases are generated, the pressure in the landfill increases, usually causing sub-surface pressures in the landfill to be higher than either the atmospheric pressure or indoor air pressure. When pressure in the landfill is higher, gases tend to move to ambient or indoor air.

- **Permeability.** Gases will also migrate according to where the pathways of least resistance occur. Permeability is a measure of how well gases and liquids flow through connected spaces or pores in refuse and soils. Dry, sandy soils are highly permeable (many connected pore spaces), while moist clay tends to be much less permeable (fewer connected pore spaces). Gases tend to move through areas of high permeability (e.g., areas of sand or gravel) rather than through areas of low permeability (e.g., areas of clay or silt). Landfill covers are often made of low-permeability soils, such as clay. Gases in a covered landfill, therefore, may be more likely to move horizontally than vertically.

Table 2-2: Factors Affecting Landfill Gas Production

Waste Composition. The more organic waste present in a landfill, the more landfill gas is produced by bacterial decomposition. Some types of organic waste contain nutrients, such as sodium, potassium, calcium, and magnesium, that help bacteria thrive. When these nutrients are present, landfill gas production increases. Alternatively, some wastes contain compounds that harm bacteria, causing less gas to be produced. For example, methane-producing bacteria can be inhibited when waste has high salt concentrations.

Oxygen in the Landfill. Only when oxygen is used up will bacteria begin to produce methane. The more oxygen present in a landfill, the longer aerobic bacteria can decompose waste in Phase I. If waste is loosely buried or frequently disturbed, more oxygen is available, so that oxygen-dependent bacteria live longer and produce carbon dioxide and water for longer periods. If the waste is highly compacted, however, methane production will begin earlier as the aerobic bacteria are replaced by methane-

producing anaerobic bacteria in Phase III. Methane gas starts to be produced by the anaerobic bacteria only when the oxygen in the landfill is used up by the aerobic bacteria; therefore, any oxygen remaining in the landfill will slow methane production. Barometric highs will tend to introduce atmospheric oxygen into surface soils in shallow portions of a landfill, possibly altering bacterial activity. In this scenario, waste in Phase IV, for example, might briefly revert to Phase I until all the oxygen is used up again.

Moisture Content. The presence of a certain amount of water in a landfill increases gas production because moisture encourages bacterial growth and transports nutrients and bacteria to all areas within a landfill. A moisture content of 40% or higher, based on wet weight of waste, promotes maximum gas production (e.g., in a capped landfill). Waste compaction slows gas production because it increases the density of the landfill contents, decreasing the rate at which water can infiltrate the waste. The rate of gas production is higher if heavy rainfall and/or permeable landfill covers introduce additional water into a landfill.

Temperature. Warm temperatures increase bacterial activity, which in turn increases the rate of landfill gas pro-duction. Colder temperatures inhibit bacterial activity. Typically, bacterial activity drops off dramatically below 50° Fahrenheit (F). Weather changes have a far greater effect on gas production in shallow landfills. This is because the bacteria are not as insulated against temperature changes as compared to deep landfills where a thick layer of soil covers the waste. A capped landfill usually maintains a stable temperature, maximizing gas production. Bacterial activity releases heat, stabilizing the temperature of a landfill between 77° F and 113° F, although temperatures up to 158° F have been noted. Temperature increases also promote volatilization and chemical reactions. As a general rule, emissions of NMOCs double with every 18° F increase in temperature.

Age of Refuse. More recently buried waste will produce more gas than older waste. Landfills usually produce appreciable amounts of gas within 1 to 3 years. Peak gas production usually occurs 5 to 7 years after wastes are dumped. Almost all gas is produced within 20 years after waste is dumped; however, small quantities of gas may continue to be emitted from a landfill for 50 or more years. A low-methane yield scenario, however, estimates that slowly decomposing waste will produce methane after 5 years and continue emitting gas over a 40-year period. Different portions of the landfill might be in different phases of the decomposition process at the same time, depending on when the waste was originally placed in each area. The amount of organic material in the waste is an important factor in how long gas production lasts.

Sources: Crawford and Smith 1985; DOE 1995; EPA 1993.

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Review

Characterisation of VOCs emitted by open cells receiving municipal solid waste

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Abstract

This study gives relevant information on the variation of concentrations of certain volatile organic compounds (BTEX, alkanes, organochlorides and terpenes) emitted by open cells receiving municipal solid waste. These compounds represent a large fraction of the total trace components present in landfill gas.

The VOC measurements were carried out in the atmosphere of an open landfill cell as a function of time and meteorological parameters, but also as a function of the activity of trucks unloading waste and compaction vehicles, in order to identify the factors that influence VOC emissions. Comparisons were performed systematically between the surface of the open cell and the corresponding mechanical activity. The measurements carried out during the course of the day highlighted the influence of air temperature and waste composition on VOC emissions while measurements of activity showed that the activity of fresh waste compaction vehicles is responsible for the highest VOC emissions. Such information is essential since most of the data in the literature relate to analyses of VOC traces in the biogas network and not in the air of the open cells as a function of different parameters (i.e. meteorological parameters, activity on the site). The highest VOC concentrations (in $\mu g/m^3$) in the area of an open cell were obtained for: tetrachloroethylene (9810), toluene (8230), limonene (4550), *m*-xylene (3980) and trichloroethylene (3680).

The results showed that the TWA values (the time-weighted average concentrations for up to an 8-h workday) established by INRS/France for the personnel in the station were complied with on the site studied.

Introduction

Burial of municipal solid waste in landfills without pre-treatment is one of the two main methods used to eliminate waste in France and will be for at least one or two decades.

In 2002, according to ADEME (Environment and Energy Management Agency), about 40% of MSW was landfilled versus 12% for recycling and 42% for incineration.

Landfill gas is produced continuously by microbial action on biodegradable wastes under anaerobic conditions. Methane and carbon dioxide are the major constituents of landfill gas and greatly contribute to the greenhouse effect [1], [2], [3], [4]. Small amounts of other gases (non-methane volatile organic compounds) are also present in landfill gas. These trace components can be formed either from intermediate biochemical reactions associated with degradation processes, or by degradation and volatilisation of other organic materials deposited in the landfill. In all, these trace components may make up less than 1–2% of the gas emitted from the waste in a landfill [2], [5]. However, the impact of certain trace gases on the environment and potentially on human health may be more significant than that of the bulk gases (e.g. CH_4 and CO_2). Over 500 compounds have been reported in landfill gas [6]. These VOC emissions include higher amounts of alkanes and alkenes, cycloalkanes and cycloalkenes, aromatic, cyclic aromatic and polycyclic aromatic hydrocarbons and derivatives, aldehydes, alcohols, ketones, esters, organohalogens and organosulphur compounds.

The main sources of these VOC emissions are: (i) faults in capping or gas collection; (ii) open leacheate chambers; (iii) faults (cracks) in the liners and covers of closed cells; (iv) open cells.

The sources of faults and cracks can only be remedied by mechanical treatment; on the contrary, VOC emissions caused by open cells are much more difficult to estimate and reduce.

Open cells are cells that receive waste arriving in a landfill and from which certain VOCs are emitted into the ambient air. Although the waste is covered by soil (e.g. clay), which helps to limit VOC diffusion, a small amount of these VOCs continues to diffuse into the ambient air. Therefore the purpose of this study was to set up a technical analytical procedure for measuring VOC emissions produced by open cells. A bibliographical study was initially carried out to guide our choice. The results of this study are presented in Table 1.

The study of these articles showed that most measurements were carried out on the landfill gas collection systems (e.g. the main line carrying gas to the engines or site flare, gas field manifolds, individual gas wells) [2], [3], [9], [11], [12], [14], [15], [17], [18], [21], [22]. Some of them [5], [8], [16]

were performed in the ambient air of the site or in the vicinity of the site, without however being positioned to evaluate the level of emission as a function of the activity of the vehicles (unloading, spreading and compaction of waste) and meteorological parameters.

Only Davoli et al. [7] have carried out several measurement campaigns of air samples from the most significant emission sources of the landfill: (i) emissions from fresh wastes (characterised by limonene); (ii) emissions from older wastes (buried before biogas collection) as well as biogas and leachate, characterised by *p*-cymene; (iii) emissions at the entrance of the landfill; (iv) emissions collected at further distances (1.5, 3 and 6km).

Another publication [23] asserts that the strongest waste odours (VOCs) are generated during discharge and compaction of waste (though gives no references or experimental results). These authors assert that disturbing waste creates new surfaces and exposes old surfaces from which volatiles can evaporate. The action of depositing more waste at each site simply results in generating more odours. However, once the waste has been compacted and covered, the rate of odour generation appears to decline rapidly. Compaction reduces the active surface available for odour generation while covering reduces the rate of volatilisation as vapour pressures develop between the waste surface and the covering layer. On the other hand, this work did not take into account the influence of ambient climatic conditions.

The study presented here comes from an ADEME thesis [24] whose objective was to investigate the emission and dispersion phenomena of certain VOCs emitted by a landfill site. It is essential to know the influence of the parameters acting on the emission of VOCs before studying their dispersion in the atmosphere.

Initially, the measurements were limited to the following chemical families: aromatics (BTEX and trimethylbenzene), organohalogens, alkanes and terpenes. These compounds are an important fraction of the total trace components present in landfill gas [6] and some of them are toxic compounds. This choice was confirmed afterwards in another study [9] based on the VOC compounds present in fresh waste. For technical reasons (i.e. poor sorption on activated carbon, etc.), the study of high volatile compounds (e.g. vinyl chloride) was excluded from the study.

Section snippets

Sampling procedure

Table 1 shows three analytical procedures: (i) sampling in canisters (or bags) without preconcentration of gas samples and laboratory analyses; (ii) sampling on sorbent tubes (or fibers) followed by laboratory analyses; (iii) on-site analysis with portable material.

Previous works [25], [26], realised in our laboratory, pointed out that sampling polluted air requires fast analysis, which is incompatible with measurements over a half-day or a whole day. Analyses with portable material under …

Choice of sampling flow

Preliminary tests were performed on site, at the edge of an open cell, using 2 different sampling rates and the same sample volume/tube: (i) 1 sample was collected through the tube “A” with a flow rate of 0.083 L/min during 120 min (sampling volume of 9.97 L); (ii) 8 different samples were taken successively, and in parallel with the sampling on tube A, with a flow rate of 0.63 L/min (sampling time/tube of 15 min, an average sampling volume per tube of 9.84 L) and a total time of 125 min for the 8 …

Conclusion

The bibliographic study showed that much research has been devoted to the identification and quantification of VOCs in the biogases of waste dumps (industrial, household waste, etc.), though few studies have been carried out on the ambient air of such sites [5], [7], [8], [10], [16], [20].

This work gives relevant information about the VOC concentration measurements on a fresh waste open cell as a function of sampling time and area of activity (unloading, spreading and compaction of waste). We …

Recommendations

The most efficient solutions for limiting the release of VOCs into the atmosphere will be those that act on the most pollutant areas: the truck tipping area and the waste compaction area. One of the solutions would be to install vaporizers on the truck tipping platforms and installing mist sprayers (with very small droplets to limit the water added to the waste) on the compactors. Another solution would be to optimise the activity of the compactors and therefore their movements, which could be …

Acknowledgements

We take this opportunity to thank ADEME which provided support to our work in the form of a grant to finance a Ph.D. thesis, and to the operator of the site who facilitated our works by making large areas of the site available to us. …

Recommended articles

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S.C. Zou *et al.*
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Insights on volatile metals in landfill gas as determined from advanced treatment media

Thomas J. Smallwood, Jordan K. Magnuson, Jake T. Thompson, Ashley M. Lin, Timothy G. Townsend

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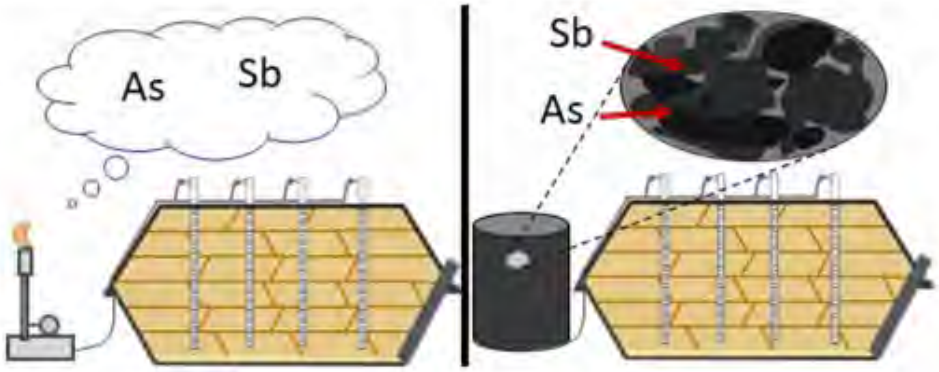
Highlights

- Activated carbon used to scrub landfill gas was measured for volatile metal concentrations.
- TCLP found the activated carbon to exceed the TC limit for arsenic by 18 times.
- Analyzed concentrations correspond to an annual emission of 23.7 kg As and 22.1 kg Sb.
- Findings suggest significant contribution from landfill gas to global As and Sb cycles.
- Study underlines the importance of landfill gas treatment to mitigate metal emissions.

Abstract

This study analyzed spent activated carbon (AC) from a landfill gas (LFG) treatment system for an expanded suite of lesser studied volatile metals, revealing elevated levels of As and Sb in the LFG, exceeding those previously reported, with minimum average concentrations of 640μgm^{-3} and 590μgm^{-3}, respectively. The annual release of As and Sb through landfill gas was found to be significant, surpassing leachate emissions by an order of magnitude. Extrapolating these findings to all US landfills suggests that the release of As and Sb through landfill gas could be a major, previously overlooked source of these metals in global emission estimates, underscoring the need to include them when developing future inventories. The spent AC was further found to exceed US toxicity limits established for As, classifying it as hazardous waste under US regulations. However, findings suggest that the AC scrubber employed at the landfill effectively prevented substantial releases of As and Sb. This research emphasizes that landfill gas is a primary contributor to environmental release of As and Sb from landfills, even more so than leachate, highlighting the significance of implementing effective LFG treatment measures to mitigate the release of volatile metal emissions.

Graphical Abstract



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Introduction

The most common environmental challenges tied to landfill gas (LFG) emissions are those associated with methane [37], trace organic pollutants [33], and in some cases hydrogen sulfide [24]. Perhaps of surprise, however, is that several trace metals and metalloids (herein simply referred to as metals) also commonly occur in the gaseous emissions from municipal solid waste (MSW) disposal sites. Much of the original focus on metals in LFG centered on mercury (Hg), and several studies have documented Hg in landfill gas at concentrations on the order of 0.0046μgm^{-3} to 13μgm^{-3} [28], [27], [40]. Though only a limited number of studies have reported metal concentrations in LFG [13], [26], [35], in addition to Hg, research has documented measurable concentrations of As, Bi, Sb, Se, Sn, Pb, M, Te, and W [9]. Most recently, de Oliveira et al. [9]

examined the presence of arsenic (As) and antimony (Sb) in LFG from landfill areas of different age and found median concentrations of 180$\mu g m^{-3}$ and 250$\mu g m^{-3}$, respectively.

Despite the paucity of available data, the presence of metals in biogas from the anaerobic biodegradation of organic wastes in landfills should be expected. Within the waste stream, discarded materials may contain metals intrinsically or through intentional addition during product manufacturing. For example, Sb and As are commonly found in textiles, wood, and plastics, which can contribute to a landfill's metal load once discarded [22], [43]. There are multiple pathways forvolatilization under landfill conditions; while inorganic Hg is volatile, under normal environmental conditions most metals will only be encountered as volatile when part of an organic compound such as dimethylmercury, trimethylarsine, dimethyl selenide, and trimethylstibine are present [4], [5], [16]. Biologically mediated methylation is a well understood conversion pathway for a wide array of metals in anaerobic environments including Hg, As, and Sb [6], [16], [30], [34]. Today the need for additional science on metals in LFG is motivated less by documenting occurrence, and more by examining the magnitude of landfill releases with respect to global metal cycles. Only by determining which metals exit landfills in environmentally consequential amounts can policy makers assess whether regulatory control is warranted, and if so, advise operators on technological improvement to reduce such release.

One limitation to the existing data on metals in LFG stems from uncertainty on the representativeness of the samples. At modern landfills, LFG is extracted from the decomposing waste mass by placing a vacuum on vertical (most common) or horizontal wells constructed into the waste mass. As a typical frequency is approximately two and a half vertical wells per hectare, large landfill sites often contain one hundred or more sampling locations. In de Oliveira et al.'s (2022) recent study, samples of LFG from 6 wells were concentrated on activated carbon for later analysis of As and antimony Sb; the total LFG volume represented in this study corresponded to less than 0.1% of the total landfill gas volume collected at this site over the sampling period. Even if a sample were collected at a single congregated exit point, only a small fraction of the volume is represented by the subsequent data.

In this paper, we report the results of a study on metals in LFG at the same landfill as de Oliveira et al. [9], taking advantage of a fortuitous opportunity at the site. The site recently began routing the majority of its LFG to a renewable natural gas (RNG) recovery plant, which refines LFG through a series of clarifying stages for eventual use as natural gas off site. An essential clarification step in this process involves passing the LFG through an activated carbon (AC) scrubber system. We collected samples of the spent AC after 37.2 million m^3 of LFG had been passed through a fixed mass of carbon and analyzed for metals. This enabled us to estimate much more robust LFG metal concentrations, and since we also had access to leachate volumes and metal concentrations, we could assess the relative concentrations of metals leaving the landfill in both LFG and leachate. With this data, we also extrapolate our observed concentrations to all US landfills to get an estimate of the annual mass release of metals through landfill gas. Finally, given that the AC does concentrate

metals, we assess the leachability of the spent AC to evaluate its potential to require management as a hazardous waste. These findings provide valuable insights into metal behavior in landfill systems and have significant implications for the appropriate management of landfill gas.

Section snippets

Sample collection

The landfill examined in this study, previously investigated by de Oliveira et al. [9], is a 33-hectare lined landfill in north Florida. According to operator provided data, the site produces approximately 102,000 m^3 of LFG daily, captured by a LFG collection system, which until spring of 2022 was managed through flaring. Recently, an RNG facility was constructed at this site and the entire LFG volume is now routed through the RNG recovery plant. A general schematic of the RNG refinement …

Results

Samples were analyzed for a suite of volatile metals. For relevance, the following results and discussion are focused on metals previously demonstrated to volatilize in landfill gas: As, Cd, Hg, Pb, Sb, Se, Sn [9], [13], [34]. Datasets related to other volatile metals which are not included below are provided for reference in the Supplementary Material. …

Conclusions

Environmental concern surrounding landfill gas emissions are typically associated with methane and other trace organic pollutants; however, other constituents like volatile metals and metalloids have been identified in landfill gas, and also pose concern. Volatilized mercury species have been the focus of the majority of original investigations on metals in landfill gas due to historic concern regarding mercury pollution, but only a handful of studies have assessed other volatile metals. …

Environmental Implications Statement

Perhaps most recognized among Toxicity Characteristic hazardous contaminants are eight metals; some of which can volatilize and have been identified in landfill gas (LFG). However, existing

research is focused on mercury, and the few studies which include other metals present highly variable/uncertain results due to small gas volumes analyzed. Here, comprehensive volatile metals, assessed from an entire LFG volume, are determined in spent media from an advanced LFG treatment process. Results …

CRediT authorship contribution statement

Thomas Smallwood: Methodology, Formal analysis, Investigation, Writing – original draft. **Jordan Magnuson**: Methodology, Validation, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Jake Thompson**: Conceptualization, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Ashley Lin**: Conceptualization, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Timothy Townsend**: Conceptualization, Resources, …

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. …

Acknowledgements

The authors would like to thank the New River Regional Landfill and Advanced Environmental Laboratories for their contributions to the publication of this work. …

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X. Chai *et al.*
The effect of aerobic conditions on the complexation ability between mercury and humic acid from landfill leachate and its implication for the environment
Chemosphere (2013)

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Landfill gas as a source of anthropogenic antimony and arsenic release
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2025, Waste Management

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Biogeochemical dynamics of major elements in municipal solid waste landfills can induce health risks for nearly 1 billion people

2025, One Earth

Show abstract

Comparative determination of the time-dependent accumulation of metal oxides in the landfill gas combustion chamber deposits using SEM-EDS, XRF and ICP OES

2024, Microchemical Journal

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A Selective and Fast Approach for Volatile Metalorganics Assaying in Wastewater

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Chemosphere

Volume 307, Part 2, November 2022, 135739

Landfill gas as a source of anthropogenic antimony and arsenic release

Fernando D.G. de Oliveira, Nicole M. Robey, Thomas J. Smallwood, Chad J. Spreadbury, Timothy G. Townsend

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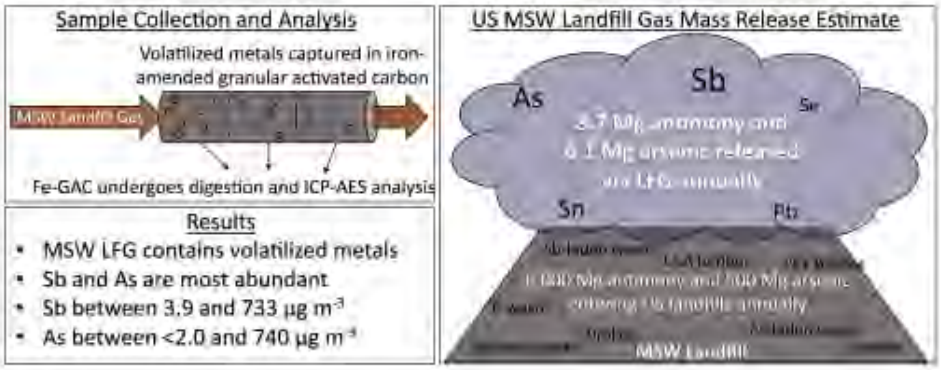
Highlights

- Wastes, including e-waste and PET bottles, contribute to landfill antimony levels.
- Volatilized metals/metalloids collected using iron-amended activated carbon.
- Gas concentrations averaged 254 μg antimony per m^3, 178 μg arsenic per m^3.
- Estimated 8.7 Mg antimony and 6.1 Mg arsenic released from US landfills annually.
- Landfill gas may contribute 4.5% of total US atmospheric antimony emissions.

Abstract

Antimony is used extensively in consumer goods, including single use plastic bottles, electronics, textiles and automobile brakes, which are disposed of in landfills at the end of their service lives. As a result, Sb is a constituent of concern in landfill emissions. Previous research has focused on leachate (liquid) and waste incineration flue gas emissions; however, Sb has the potential to volatilize through chemical and microbial processes within a landfill. In this study, iron-amended granular activated carbon was used to adsorb volatile metals directly from gas in a full-scale landfill gas collection system. Metals were quantified using acid digestion and ICP-AES analysis. Antimony concentrations far exceeded those previously reported, at up to 733 $\mu g m^{-3}$ (mean: 254 $\mu g m^{-3}$). In addition to Sb, As was also measured at high levels compared to previous research, as high as 740 $\mu g m^{-3}$ (mean: 178 $\mu g m^{-3}$). Using US EPA landfill and landfill gas databases, total Sb emissions via landfill gas are estimated to be approximately 27.3 kg day^{-1} in the US. Based on other estimates of national and global Sb emissions, this corresponds to approximately 4.5% of total US atmospheric emissions of Sb and 0.42% of global atmospheric emissions. Sb mass release via landfill gas is approximately 3.9 times higher than via leachate emissions. Although gas emissions are higher than expected, the vast majority (99.9%) of Sb present in landfilled MSW remains within the waste mass indefinitely. In addition to these mass release estimates, this experiment suggests that iron-amended activated carbon may offer significant metals removal from LFG, especially in the first months of new well operation.

Graphical abstract



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Introduction

Over 40,000 tons of antimony (Sb), a metalloid in the same elemental class as arsenic (As), are used in consumer goods in the US annually (Krenev et al., 2015), added to consumer products such as textiles, brake pads, and electronic plastics as a coloring agent or flame retardant (Alassali et al., 2019; Filella et al., 2020; Morf et al., 2007; Robinson, 2009). At the end of their service life, most of these consumer goods are disposed of in landfills (US EPA, 2020a). In a study of trace metal

presence in 22 municipal solid waste (MSW) categories, Sb concentrations from 1.3 to 21,000 $mg\,kg^{-1}$ were measured in different waste components, with polyethylene terephthalate (PET) plastics identified as the most significant sources of Sb (Filella, 2020; Tucker et al., 2020). Other research which focused on E-waste, which is likely to contain Sb added as a flame retardant to the plastics and circuit boards, measured levels between 1700 and 50,000 $mg\,kg^{-1}$ (Ernst et al., 2003; Intrakamhaeng et al., 2020a; Morf et al., 2007; Turner and Filella, 2017). Under landfill conditions, Sb leaches from these products and has been measured at levels exceeding risk-based thresholds in MSW landfill leachate (Intrakamhaeng et al., 2020a; Moody and Townsend, 2017). Because Sb has been identified as a probable human carcinogen by the International Agency for Research on Cancer (IARC) and as a priority pollutant by the US Environmental Protection Agency (US EPA) (Jenkins et al., 2007; Saerens et al., 2019; US EPA, 2012), the release of Sb from MSW landfills has been a focus of emerging regulatory and scientific interest. Existing research has concentrated on MSW landfill leachate (liquid) and volatilization through MSW incineration (Filella et al., 2020; Okkenhaug et al., 2015).

MSW landfill gas (LFG) consists predominantly of methane (CH_4) and carbon dioxide (CO_2) generated by the decomposition of organic matter, but other trace constituents are present (Allen et al., 1997; Assmuth and Kalevi, 1992; Eklund et al., 1998; Wang et al., 2021). Metals known to volatilize under anaerobic conditions have also been reported in LFG, and past research has focused on Hg, Pb, and As in particular (Feldmann and Hirner, 1995; Hirner et al., 1994; Michalke et al., 2000; Olson et al., 2003; Pécheyran et al., 1998; Sevimoglu and Tansel, 2013). Comparatively few studies have investigated Sb emissions in LFG, likely because it has historically been considered a lower priority pollutant and because it was not used as extensively in consumer products until the increase in household electronics seen in recent decades (Nishad and Bhaskarapillai, 2021).

Volatile As and Sb occur in both the inorganic form (arsine (AsH_3) or stibine (SbH_3)) and as methylated varieties (mono-, di-, or trimethylarsine/stibine) (Caplette and Mestrot, 2021; Wang et al., 2014). As and Sb volatilize as a result of microbially-mediated landfill processes that previous studies have documented in MSW landfills and the volatilized species may be transported from the landfill through LFG (Caplette and Mestrot, 2021; Feldmann et al., 1994, 1998; Feldmann and Cullen, 1997; Feldmann and Hirner, 1995; Hirner et al., 1994; Pinel-Raffaitin et al., 2007). Feldmann and Hirner (1995) reported the presence of Sb in landfill gasses in concentrations ranging 24–72 $\mu g\,m^{-3}$, and Feldmann et al. (1999) reported Sb concentration in sewage and landfill gas ranging between 0.04 and 84 $\mu g\,m^{-3}$ of LFG. Hirner et al. (1994) used a cryogenic trap to adsorb gas from domestic waste deposits and reported Sb values ranging from 0.04 to 2.4 $\mu g\,m^{-3}$ of LFG. These studies were the first to report Sb in landfill gas, and it is expected that the use of Sb and the composition of MSW itself has changed significantly in the intervening decades and merits revisiting.

Here, we describe an experiment where volatilized metals were extracted directly from LFG in a gas control and collection system of a full-scale MSW landfill using iron-amended activated carbon sorption followed by quantitation using acid digestion and ICP-AES analysis. Activated carbon has

been used extensively to remove several contaminants from groundwater, drinking water and wastewater (Appleman et al., 2013; Chávez et al., 2019; Depci, 2012; Huang and Fu, 1984), and iron-impregnated GAC is especially effective for As removal due to the surface interaction with iron (Chen et al., 2007; Gu et al., 2005; Huang and Vane, 1989; Jang et al., 2008; Muñiz et al., 2009; Reed et al., 2000; Zhang et al., 2007), with similar effectiveness reported for Sb removal (Zhu et al., 2021). While most MSW landfills do not require treatment system for LFG, iron-amended GAC is currently used at some sites to remove hydrogen sulfide (Choudhury and Lansing, 2021; Ciahotný and Kyselová, 2019; Xiao et al., 2008).

To understand the potential impacts of metals (Sb, specifically) released from MSW landfills via LFG, concentrations measured in the LFG were used to estimate a total mass of volatilized Sb released to the environment. The total mass of Sb released was evaluated on a national scale in comparison to other landfill effluents, for example leachate, and industrial practices, such as mining, coal-fired plants, incineration facilities and smelters (ATSDR, 2019; Nishad and Bhaskarapillai, 2021; Tian et al., 2014). Concern over As, historically added to wood as a preservative and similar to Sb in property and oxyanion behavior, led to industry-wide changes and, over time, a reduced presence in the waste stream (Jones et al., 2019; Robey et al., 2018; Tolaymat et al., 2000). Conversely, Sb applications in consumer products and concentrations in waste have increased over time (Intrakamhaeng et al., 2020a, 2020b; Morf et al., 2007; Robinson, 2009; Tostar et al., 2013; Turner and Filella, 2017), corresponding with renewed concern over environmental emissions.

Section snippets

Materials and methods

Metals were extracted from MSW LFG using iron-impregnated granular activated carbon (GAC) and quantified using an acid digestion followed by inductively coupled plasma – atomic emission spectroscopy (ICP-AES). The mass of metals in the GAC and corresponding LFG volumes were used to calculate concentrations of volatilized metals in the LFG. …

Metals concentrations in LFG

Metals which have been demonstrated to volatilize (in the environment or under landfill conditions), As, Cd, Pb, Sb, Se, and Sn, were quantified in the GAC (Mason, 2012; Pécheyran et al.,

1998). Previous studies which conducted speciation analysis of volatilized metals found that methylation is the primary mode of volatilization (Mason, 2012), trimethylarsine ($As(CH_3)_3$) was the dominant volatile arsenic species measured in LFG (Pinel-Raffaitin et al., 2007). All elements except for Cd were …

Conclusions

This study presents the results of a novel technique to quantify volatilized metals in LFG, as well as important Sb and As emissions data collected from a full-scale, operational MSW LFG collection and control system. These findings add to the understanding of Sb emissions resulting from landfill management of MSW in the US. Although Sb has been known to volatilize under landfill conditions, recent changes in the use of Sb in consumer goods and the profile of MSW have contributed to new concern …

Credit author statement

Fernando D.G. de Oliveira: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Visualization, Nicole M. Robey: Validation, Formal analysis, Writing – review & editing, Visualization, Thomas J. Smallwood: Investigation, Validation, Writing – review & editing, Chad J. Spreadbury: Writing – review & editing, Timothy G. Townsend: Conceptualization, Methodology, Writing – review & editing, Supervision, Funding acquisition. …

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. …

Acknowledgments

This work was supported by funding from the New River Solid Waste Association. …

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2024, Journal of Hazardous Materials

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Ecotoxicological impacts of landfill sites: Towards risk assessment, mitigation policies and the role of artificial intelligence

2024, Science of the Total Environment

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Didactical approaches and insights into environmental processes and cardiovascular hazards of arsenic contaminants

2024, Chemosphere

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Per- and polyfluoroalkyl substances (PFAS) distribution in landfill gas collection systems: leachate and gas condensate partitioning

2023, Journal of Hazardous Materials

> *Citation Excerpt :*
>
> …BOD, which makes up a fraction of COD and is a measurement of biologically available organic matter, averaged 139 mg L−1 in the three LGC samples for which BOD was measured, and 962 mg L−1 in the GWP samples (n = 5). While metals concentrations in the GWP were typical of MSW leachate [24,26,35,58], nearly all metals were significantly lower or below detection limits in the LGC samples – with the exception of arsenic and antimony, two metalloids which have been previously reported in MSW landfill gas [40,13,21]. Arsenic concentrations ranged between 0.034 mg L−1 and 0.85 mg L−1 (mean: 0.47 mg L−1) in the GWP and between 0.055 mg L−1 and 2.85 mg L−1 (mean: 1.06 mg L−1) in the LGC.…

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Microplastics and adsorbed micropollutants as emerging contaminants in landfill: A mini review

2023, Current Opinion in Environmental Science and Health

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Neutral Per- and Polyfluoroalkyl Substances in In Situ Landfill Gas by Thermal Desorption-Gas Chromatography-Mass Spectrometry

2023, Environmental Science and Technology Letters

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Waste Management

Volume 119, 1 January 2021, Pages 39-62

Review

Trace gas emissions from municipal solid waste landfills: A review

Zhenhan Duan, Charlotte Scheutz, Peter Kjeldsen

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Highlights:

- Uncovered waste surfaces are the most important emission sources for trace gases.
- Landfills with non-source-separated waste and poor management give high emissions.
- Geomembranes/biocovers are more efficient in reducing fugitive trace gas emissions.
- Trace gases pose risks to human health and the environment in some countries.

Abstract

Trace gas emissions from municipal solid waste (MSW) landfills have received increasing attention in recent years. This paper reviews literature published between 1983 and 2019, focusing on (i) the

origin and fate of trace gas in MSW landfills, (ii) sampling and analytical techniques, (iii) quantitative emission measurement techniques, (iv) concentration and surface emission rates of common trace compounds at different landfill units and (v) the environmental and health concerns associated with trace gas emissions from MSW landfills. Trace gases can be produced from waste degradation, direct volatilisation of chemicals in waste products or from conversions/reactions between other compounds. Different chemical groups dominate the different waste decomposition stages. In general, organic sulphur compounds and oxygenated compounds are connected with fresh waste, while abundant hydrogen sulphide, aromatics and aliphatic hydrocarbons are usually found during the methane fermentation stage. Selection of different sampling, analytical and emission rate measurement techniques might generate different results when quantifying trace gas emission from landfills, and validation tests are needed to evaluate the reliability of current methods. The concentrations of trace gases and their surface emission rates vary largely from site to site, and fresh waste dumping areas and uncovered waste surfaces are the most important fugitive emission sources. The adverse effects of trace gas emission are not fully understood, and more emission data are required in future studies to assess quantitatively their environmental impacts as well as health risks.

Introduction

As a result of global economic development, population growth and urbanisation, more and more municipal solid waste (MSW) is generated each year around the world. According to the World Bank, 2.01 billion tonnes of MSW was generated in 2016, and up to 3.40 billion tonnes will be generated by 2050 under a business-as-usual scenario (Kaza et al., 2018), which will pose great challenges for governments. Among the various waste treatment and disposal methods, landfilling is the leading method in most countries, especially in low-income and upper-middle-income countries (Kaza et al., 2018). On a global level, about 70% of all generated MSW is disposed in some sort of landfill (sanitary and unsanitary landfills, open dumps) (Fischedick et al., 2014, Kaza et al., 2018). Whereas landfilling type (either controlled or uncontrolled) as well as disposed waste composition differ from country to country, short- and long-term gaseous emissions – alongside associated human health and environmental risks – represent one of the biggest concerns. Raw landfill gas (LFG) or source gas, normally consisting of 50–60% methane and 40–50% carbon dioxide, is generated from the biodegradation of disposed organic matter inside the landfill. In addition, LFG also contains hundreds of different compounds in trace amounts (combined ~1% in the total volume and referred to as ‘trace gases’), originating either from disposed waste products and hazardous waste and/or from waste degradation processes occurring in the landfill body (US US EPA, 1997, Young and Parker, 1983).

Although trace gas emissions represent only a very small portion of the overall emission from landfills, they continue to be a concern, due to the adverse effects on the environment and human health. Compounds, such as benzene and vinyl chloride, are carcinogenic to humans, and it is also

widely recognised that sulphur compounds, together with some oxygenated compounds and hydrocarbons, are responsible for the offensive odours emanating from landfills. Moreover, emissions of chlorofluorocarbons and halocarbons contribute to ozone depletion and global warming (Licata and Minott, 1996), and some alkanes and aromatics combine with nitrogen oxides in the atmosphere to form secondary air pollutants (Canzano et al., 2010).

In the 1970s and 1980s, research on trace gas emissions from MSW landfills was carried out in the United States and some European countries (Parker et al., 2002, Shen et al., 1990). The topics included trace gas composition and concentrations in raw LFG and in ambient air from distinct locations at a landfill site, trace gas sampling and analytical techniques, emission rate measurements, odour and health risk assessments, etc. Landfill gas composition and trace gas concentrations were extensively explored and reported. Emission rates as well as emission factors (in $\mu g\ s^{-1}$ or $\mu g\ m^{-2}\ min^{-1}$) for a range of trace gases from MSW landfills were established by the United States Environmental Protection Agency (US EPA) (e.g. the EPA AP-42 default values) (US EPA, 1995a, US EPA, 1995b, US EPA, 1997). Research published before 2002 was reviewed by Brosseau and Heitz (1994), Hamideh Soltani-Ahmadi, 2000, Parker et al., 2002.

In the late 1990s, a sharp decline in trace gas emissions was observed from MSW landfills in the US compared to the EPA AP-42 default values, mainly due to the implementation of the US EPA's Resource Conservation and Recovery Act's (RCRA) hazardous regulations leading to reduced amounts of hazardous waste entering these sites (Hamideh Soltani-Ahmadi, 2000, Staley et al., 2006). Similarly, the European Union released the Landfill Directive (CEC, 1999) in 1999, which has since contributed to a steady decrease in biodegradable waste going into landfills and at the time was also expected to reduce trace gas emissions significantly (European Environment Agency, 2016, Pawlowska et al., 2008). Hence, data reported before 2000 do not represent the current status, and there is a need to update knowledge on trace gas emissions from landfills in those countries. In recent years, there has been rising concern in developing and middle-income countries, such as in China, about the potential risks caused by trace gas emissions from MSW landfills. The lack of source segregation, and the high organic content of landfilled waste as well as improper site operations in some countries, has exacerbated trace gas emissions, potentially causing excess health risks to surrounding populations (Liu et al., 2016a, Tian et al., 2013).

An increasing number of studies on trace gas emissions from MSW landfills have been published within the last 10years, and large amounts of data on trace gas composition, concentrations and their associated environmental and health risks have been reported globally (Fig. 1). However, most of the data focused on trace gas concentrations measured at different landfill units, which are difficult to compare with each other, and trace gas emission rates from MSW landfills were rarely reported. In addition, these studies have focused on different compounds, making it challenging to understand the dominant chemical groups on a general level. Hence, a new review paper is in need, to provide an overview of the current trace gas emission status at MSW landfills, to update and compare data from studies in both developed and developing countries, to provide insights into

related environmental impacts and health risk assessments and to identify future research needs in this field.

This review article includes six sections based on studies published in 2003–2019. It discusses the origin and fate of trace gases in MSW landfills, before moving on to introduce and discuss the sampling and analytical techniques as well as quantitative emission rate measurement techniques. Concentrations of some common trace compounds in raw LFG and in ambient air at different landfill units are reported and compiled, and fugitive emission rates of trace gases from previous studies are summarised and compared for different landfill surfaces. In addition, a review on the adverse impacts of trace gas emission is undertaken, concentrating on factors such as human health risks, odour pollution, stratospheric ozone depletion, climate change and air pollution. Finally, research needs are identified for future studies on trace gas emissions from MSW landfills.

Section snippets

Definition of landfill trace gases

Landfill trace gases are gaseous compounds present in trace amounts (a total volume fraction of up to 1%) in raw LFG. In previous studies, trace components present in raw LFG were named ‘non-methane organic compounds’ (NMOCs), ‘non-methane hydrocarbons’ (NMHCs), ‘volatile organic compounds’ (VOCs), ‘volatile compounds’ (VCs) or ‘odorous compounds’ (OCs), depending on the target compounds and the focus of the study. In this paper, we use the term ‘trace gases’, which mainly refers to VOCs but …

Sampling and analytical techniques

Proper sampling is fundamental for measuring landfill trace gas concentrations and quantifying emission rates. The sampling procedure must be carefully designed to ensure that representative samples are taken and properly stored, thus avoiding any loss or alteration in the composition and concentration so that they reflect the real state of the monitored air or gas. Precise analytical techniques are also necessary, especially when considering the low concentration levels and diverse chemical …

Quantitative measurement of trace gas emissions from MSW landfills

Emission rates or surface emission fluxes are often necessary to determine environmental impacts and human health risks, as well as to monitor the results of pollution control activities (Canzano et al., 2010, Kim, 2016). Emission rates are also input data for most air dispersion models (including odour dispersion models) when estimating the downwind concentration of certain pollutants and defining the safe distance between landfills and residential areas (De Melo Lisboa et al., 2006, Murthy …

Trace gas constituents and concentrations in MSW landfills

According to the relevant information given in the literature (2003–2019), concentration data of 63 common trace compounds are compiled in this section (see Table S1). Previous studies have reported concentration data for hundreds of trace compounds; however, in this paper it was decided to focus on those 63 compounds as they were frequently reported in literature and their concentrations contribute most to the total trace gas concentrations in LFG. Hence, the conclusions made in this section …

Reported fugitive emission rates of trace gases from different landfill surfaces

As has been discussed in Section 4, the quantitative measurement of trace gas emission rates from landfill surfaces is a challenging task, and only a few publications have reported in this regard. Table 3 summarises the reported emission rates from studies published after 2002, and most of the measurements were conducted by using surface flux chambers, particularly static chambers. Detailed concentration data for individual compounds and relevant landfill information can be found in Table S3 …

Trace gas dispersion in the atmosphere, and environmental concerns

To evaluate the environmental impacts and health risks of an existing or planned landfill site, it is necessary to monitor the dispersion of trace gases in the atmosphere. This is normally done by using air dispersion models, which include simple or advanced Gaussian plume models, sophisticated Lagrangian particle models, Eulerian grid models (3-D models) and the most complicated computational fluid dynamics (CFD) models (Capelli et al., 2013b). The most widely used options are Gaussian plume …

Conclusions

In recent years, concern has grown regarding trace gas emissions from municipal solid waste (MSW) landfills. This paper provides an overview of the origin, transportation and emission of these gases in landfill environments, the concentration ranges of common trace gases in raw landfill gas (LFG) and in ambient air above different landfill units, their fugitive emission rates from landfill

surfaces and the resulting environmental impacts. In addition, gas and air sample collection, analytical …

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. …

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