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The impact of landfill management approaches on methane emissions

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Abstract

This article reports on how management approaches influence methane emissions from landfills. The project team created various landfill operational scenarios for different regions of the planet with respect to waste composition, organic waste reduction and landfill gas recovery timing. These scenarios were modelled by applying a basic gas generation model according to the United Nations Intergovernmental Panel on Climate Change (IPCC) recommendations. In general, the IPCC's recommended modelling parameters and default values were used. Based on the modelling undertaken, two options stand out as being the most effective methane mitigation measures in a wide range of conditions throughout the world: (a) early gas recovery and (b) reduction of the amount of biodegradable organic waste accepted in a landfill. It is noted that reduction of organic input to any given landfill can take many years to realize. Moreover, suitable alternative processing or disposal options for the organic waste can be unaffordable for a significant percentage of the planet's population. Although effective, organic waste reduction cannot therefore be the only landfill methane mitigation measure. Early landfill gas recovery can be very effective by applying basic technologies that can be deployed relatively quickly, and at modest cost. Policymakers and regulators from around the globe can significantly reduce adverse environmental impacts from landfill gas emissions by stimulating both the early capture and flaring and/or energy recovery of landfill gas and programmes to reduce the inflow of organic waste into landfills.

Keywords

Landfill, methane, emission, mitigation, management, gas recovery

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Introduction

Methane is generated in and emitted from landfills by anaerobic decay of degradable organic carbon (DOC) present in the waste disposed in landfills. Waste management, in particular the disposal of municipal solid waste (MSW) in landfills, constitutes the world's third largest anthropogenic source of methane emissions after fossil fuels and enteric fermentation plus manure from livestock. It amounts to 18% of the total global anthropogenic methane emission and to 3.8% of the total global greenhouse gas (GHG) emissions (Intergovernmental Panel on Climate Change (IPCC), 2021). Methane has an estimated mean half-life of 9.1 years in the atmosphere (IPCC, 2013) and is therefore a contributor to global warming for a relatively brief period following its release. Methane has a global warming potential (GWP) 28 times greater than CO_2 for a 100-year time frame (IPCC, 2013; UNFCCC, 2021). However, over a 20-year time frame, the GWP of methane is approximately 84 times greater than CO_2 (Wedderburn-Bishop et al., 2015). Consequently reducing methane emissions from landfills will significantly reduce global radiative forcing. The 112 nations that launched the Global Methane Pledge (2021) at COP 26 agreed 'to take voluntary actions to contribute to a collective effort to reduce global methane emissions at least 30 percent from 2020 levels by 2030'.

Globally approximately two thirds of MSW is landfilled (Kaza et al., 2018). The IPCC (2022) recommends the reduction of organic waste to landfill as the primary methane mitigation measure that could be undertaken by the waste management sector. In recent years, waste policies that mandate a reduction of food waste have been explored by local authorities in Asia, Europe and North America. Due to widely varying MSW management practices and resource limitations around the world, full

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enforcement of an organics to landfill reduction policy will be a lengthy process (e.g. UNEP, 2017). Practical experience of the authors indicates that siting, environmental impact assessment, design, permitting, financing and construction of waste treatment plants to treat the organic waste diverted from landfills can take many years and has a significant cost. In Europe biodegradable MSW to landfill reduction has been mandatory since 2001 (European Commission, 1999). Yet in the last decade, MSW landfilling has only dropped from 33% to 23% of MSW generation (Eurostat, 2022). The World Health Organization (WHO) (MacFarlane, 1996) found that irrespective of culture, societies are not prepared to spend more than approximately 0.5% of their gross domestic product (GDP) on waste management. Reduction of organic wastes disposed of in landfills requires some combination of separate collection, mechanical separation, composting, fermentation and/or incineration, coming at an annual cost of approximately US$ 100 per capita (including the cost incurred by commerce and industry). The WHO rule of thumb requires an average GDP per capita of approximately US$ 20,000 per year to afford a comprehensive organic waste to landfill reduction programme. Various sources (CIA, 2022; IMF, 2022; World Bank 2022) list the GDP at purchasing power parity (GDP-PPP). Taking the average from these sources indicates that almost 60% of all nations has a GDP-PPP below that level. Consequently, it cannot be considered realistic that these nations can afford state-of-the-art alternatives for organic waste to landfill disposal within the next decade.

The lengthy process and the high cost of alternative treatment for biodegradable wastes will inhibit achieving the goals of the Global Methane Pledge in 2030. The problem definition for this study is: can additional landfill operational mitigation measures, that are effective and can be rapidly deployed, be identified? The practitioners of the International Solid Waste Association (ISWA) Working Group on Landfill (WGL) have valuable insight and experience with management approaches in different operational phases of landfills. The ISWA WGL initiated a project to quantify the impact of different management approaches on landfill gas recovery at landfills. The goal of this project was to compile factual arguments to illustrate and clarify to both regulators and operators, which realistic management approaches during landfill operation provide an opportunity to minimize GHG emissions over its lifetime in relevant regions on the planet.

Materials and methods

General

A literature review or a comparison of landfill (pilot) projects was not considered feasible for this article as the landfill operational conditions are usually poorly described. It was therefore decided to determine the impact of different landfill gas operational scenarios by means of modelling according to IPCC recommendations (IPCC, 2006, 2019). With the exception of Antarctica (few landfills, low methane generation, no IPCC recommendations) plausible scenarios for each continent were compiled. The scenarios were described in terms of input parameters that allow for modelling according to IPCC recommendations (Figure 1). The modelling results provide the GHG emission impact of realistic management approaches for the different continents. In accordance with current IPCC and UNFCCC practice, carbon neutral was adopted for biogenic carbon dioxide, and the focus was on methane in the landfill gas. The IPCC considers the amount of nitrous oxide in landfill gas negligible (IPCC, 2006), so this was not considered. Some landfills can have relatively high concentrations of chlorofluorocarbons (CFCs) that can contribute up to 10% of the landfill's GHG emissions. This is rare and was therefore not considered in a generic modelling approach. As CFCs are being phased out by the Montreal Protocol (UNEP, 1987), they will constitute a decreasing proportion in landfill gas. Recently more information has become available on carbon black (soot) as GHG (Paul, 2021). Among others, carbon black is emitted from landfill fires. ISWA (2019) discourages landfill fires and open waste burning for health reasons. Carbon black was therefore also excluded from the project approach.

Model

There are numerous landfill gas generation models available. Not all models are accessible or transparent or have been published in scientific and technical articles. The IPCC recommendations have the highest authority and credibility and are based on a first-order degradation model. The model is used by nations to report together the GHG emissions of all landfills present in that nation to the UNFCCC. The model does not allow for differentiation in landfill operational phases. Consequently, it was decided to use the 'Afvalzorg simple landfill gas model' (Afvalzorg, 2021). This model follows the IPCC recommendations, is open source and is updated for the IPCC 2019 refinement (IPCC, 2019). The model also allows for the calculation of distinct emissions from different landfill cells as they are being constructed, filled and covered consecutively, and to attribute different recovery rates for individual cells and for every year of operation, closure and post-closure care of each cell.

Aspects of a landfill scenario

A landfill scenario typically consists of the operational aspects (an annual amount of waste landfilled, the number of years that annual amount is landfilled and the waste types), the climatic conditions, degradation parameters and the level of gas control (Figure 1). A detailed description of the background and relevance of these aspects is provided in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 5: Waste (IPCC, 2006) and the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 5: Waste (IPCC, 2019).

Operational aspects. The United Nations (2018) estimated that 55% of the world population lives in an urban environment in 2018, and this will grow to 60% by 2030 and 70% by 2050. This implies that the main landfill GHG impact (as well as hazards and nuisances) comes from urban areas, and increasingly less from rural areas. It was therefore decided to focus on urban areas

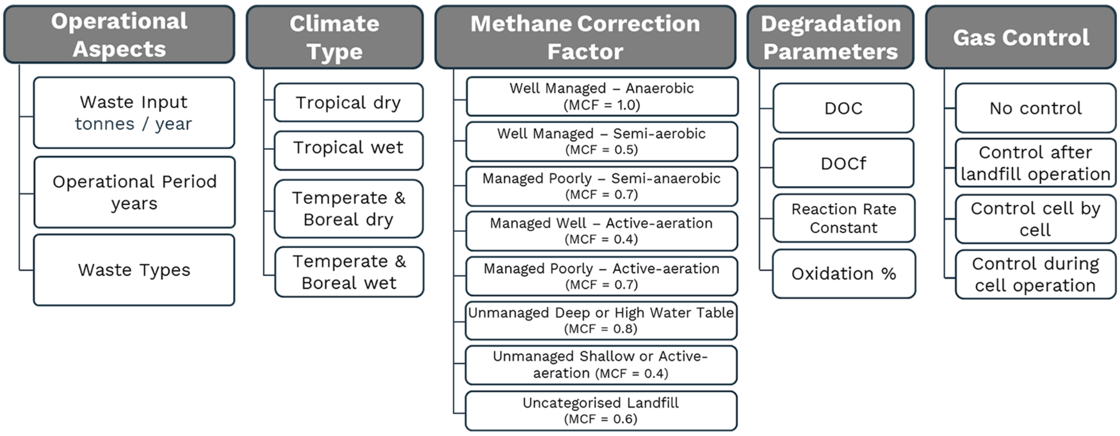

Figure 1. Input parameters (allowing methane generation modelling) describing scenarios.

only for this article. For reasons of comparability, it was decided to model a waste input of 500,000 metric tonnes per year for a period of 30 years for all scenarios. For Africa, a 40-year period was considered more realistic.

Where possible and appropriate waste types and composition were based on official documents (see Table 4). In some cases, the data were complemented with expert judgement (i.e. author's experience).

Climate. The rate at which DOC decomposes varies according to the local climate. The IPCC distinguishes between four different climate categories (IPCC, 2006): 'boreal and temperate/dry', 'boreal and temperate/wet', 'tropical/dry' and 'tropical/wet'. In Oceania, large urban landfills primarily are present in New Zealand and the east coast of Australia. Based on the Köppen climate classification (Kottek et al., 2006), this allows for a similar climatic classification to be used for New Zealand and Australia, that of 'boreal and temperate/wet'. The Asian scenarios focus on South East Asia and consequently have a 'tropical/wet' climate. Europe falls in the IPCC climate categories 'boreal and temperate, wet' or 'boreal and temperate/dry' (SAGE, 2022). Regarding the African continent, two major climate zones can be identified (SAGE, 2022): the northern and southern parts can be considered 'tropical/dry', whereas the central part of the continent can predominantly be regarded as 'tropical/wet'. Large parts of South America and the Caribbean (SAGE, 2022) can be considered 'tropical/wet' and 'tropical/dry'. For the populous portions of Canada, United States of America and Mexico, the authors deemed the categories 'boreal and temperate/wet' or 'boreal and temperate/dry' most appropriate. Consequently, all IPCC climate categories are represented in the study.

Methane correction factor. In order to apply the appropriate methane correction factor (MCF), IPCC (for detailed explanation see IPCC, 2006, 2019) distinguishes between eight different types of landfill management (Figure 1). Urban landfills with an annual input of around 500,000 tonnes are large and usually have a waste depth greater than 5 m. Therefore, the focus for this modelling exercise is on managed – anaerobic landfills (MCF = 1.0). In addition, for Africa, unmanaged deep landfills are also considered (MCF = 0.8).

Degradation parameters. In practice, landfills will receive different waste types with different DOC contents at different times. The IPCC (2019) distinguishes between three different types of DOC: highly, moderately and less decomposable. Not all DOC decays under landfill conditions. For each of the three types of DOC the IPCC (2019) has defined a DOCf: the fraction of the DOC that actually decays in the landfill. The model that was selected is a so-called single phase model. This means that the model calculations are executed with one single (weighted average) value for DOC × DOCf. In order to both accommodate the typical waste mixture for each continent and the calculation of impact due to landfill diversion policy, weighted averages of DOC × DOCf and *k*-values (degradation rates) were calculated (see repository: https://we.tl/t-2feXSc2lbN) with IPCC default values and recommendations based on waste types (IPCC, 2006, 2019). In some cases, national recommendations deviating from IPCC defaults were used as long as they were within the range mentioned by IPCC. An example for the calculation of weighted averages of DOC × DOCf and *k* in a baseline scenario (i.e. current waste composition) for a tropical wet climate is presented in Table 1.

Part of the generated methane that is not recovered might be oxidized microbially in a suitable landfill cover. In such cases, the IPCC (2006) recommends that a 10% oxidation rate of the methane generated minus the methane recovered be applied. If such a cover is not in place, the IPCC (2006) recommends 0% oxidation. Both were applied where considered appropriate in the scenarios.

Gas control. The IPCC landfill gas recovery default value for National Inventory Reports (NIR) is 20% of the methane generated (IPCC, 2006). This value allows a nation to include a relatively large number of abandoned landfills without recovery in addition to operational landfills with gas recovery in the NIR.

Table 1. Calculation of weighted averages of DOC × DOCf and k for a tropical wet climate.

Waste category	%	Waste mass (tonnes year^{-1})	DOC (wet basis)	DOCf	DOC × DOCf (per tonne)	*k* Tropical/ wet	Contribution to *k*
Food waste	52	260,000	0.150	0.7	0.055	0.400	0.208
Paper and card	13	65,000	0.400	0.5	0.026	0.070	0.009
Wood	1	5,000	0.430	0.1	0.000	0.035	0.000
Industrial	15	75,000	0.150	0.5	0.011	0.170	0.026
Non-degradables	19	95,000	0.000	0.0	0.000	0.000	0.000
Total	100	500,000			0.092		0.243

Table 2. Typical modes of gas control.

Gas control	% Gas recovery	Remark
No gas control	0	
Passive control	10–30	
Late control after operation (years 32–100)	50–90	The actual recovery efficiency depends on the gas permeability of the temporary or permanent cover and can vary based on the expert's judgement
Standard control cell by cell (from year 4 onwards)	50–90	
Early control during filling (from year 1 onwards)	10–90	

Consequently, this IPCC default value is not appropriate for modelling of individual landfills with gas recovery. Landfill operators can choose various management approaches that influence the methane recovery efficiency and the moment when methane recovery starts. These are aspects like cell size, when to install wells, what type of wells to install, when to start recovery, how to control recovery (gas quality or gas quantity), when to put (or not put) in a capping or surface sealing layer, when to end recovery, what kind of passive treatment to realize and so on. Gas recovery during waste placement can be done by means of horizontal gas wells or by regularly extended vertical wells. These wells and conveyance pipework are more prone to damage by settlement and risk impact from vehicles. Early gas recovery has however been practiced widely and proven feasible on operational landfills. In order to limit the number of options, this modelling exercise distinguished between no gas control, passive gas control, late gas control (after the total landfill volume has been filled), standard gas control (after each landfill cell is filled) and early gas control (during disposal) (Table 2).

Experience shows that a recovery efficiency of 90% or more can only be achieved by over-extraction or by installing an impermeable surface sealing layer. In some scenarios, installing surface sealing layers is considered and explicitly mentioned.

Landfill management approaches

Reduced DOC content. Lowering the DOC input of the landfill normally is not a choice made by the landfill operator, but by the regulator. In order to compare scenarios, it was decided to illustrate this impact by designing scenarios according to government policy or reductions considered realistic by the authors for each continent.

The Climate Change Commission report for New Zealand (2021) advised that organic waste to landfill must be reduced by 50% by 2035. The Australian National Waste Policy Action Plan (2019) advises a 50% diversion of organics from landfill by 2030. For South East Asia, a food waste reduction of 20% is assumed as a conservative approach as food separation is relatively new in Asia. The new European target is to reduce landfill by 2035 to less than 10% of the biodegradable MSW that was landfilled in the baseline year. For Africa, a 10% food waste reduction was chosen. Brazil, the country with the largest population in South America, has set a target to reduce 8% of total waste disposed of by 2032 (Brasil, 2022). A reduced organic scenario for North America assumed bringing the amount of degradable carbon down by 43%. All reduced organics scenarios assumed the reduction to be effective immediately.

Organic waste reduction policy is often the same as a landfill diversion policy. If for example, it is assumed that 15% reduction of food waste is achieved, 15% of 260,000 tonnes of food waste per year (in Table 1) represent 40,000 tonnes of food waste per year. To account for landfill diversion in this study, the total amount of waste landfilled is reduced from 500,000 to 460,000 tonnes per year. The percentage of food waste in the mixture goes down, and the percentages of the other waste categories go up. The resulting weighted averages of reduced DOC × DOCf and *k* for a tropical wet climate are presented in Table 3.

Landfill gas recovery. Recovery efficiencies for all scenarios are presented in Table 4. In New Zealand, early gas recovery is already required by current legislation. It was assumed that progressive final capping would take place after a further 10 years, increasing the recovery efficiency to 90%. In Australia, early gas recovery is not legislated but driven by local compliance. The worst case scenario of gas wells being installed once the landfill is full and the entire landfill has reached its final height was assumed as the baseline scenario. Early gas recovery in Australia is assumed to follow the New Zealand approach.

Table 3. Calculation of weighted averages of reduced DOC × DOCf and *k* for a tropical wet climate.

Waste category	%	Waste mass (tonnes year^{-1})	DOC (wet basis)	DOCf	DOC × DOCf (tonne^{-1})	*k* Tropical/ wet	Contribution to *k*
Food waste	48	220,000	0.150	0.7	0.050	0.400	0.191
Paper and card	14	65,000	0.400	0.5	0.028	0.070	0.010
Wood	1	5,000	0.430	0.1	0.000	0.035	0.000
Industrial	16	75,000	0.150	0.5	0.012	0.170	0.028
Non-degradables	21	95,000	0.000	0.0	0.000	0.000	0.000
Total	100	460,000			0.091		0.229

In Southeast Asia, a 50% recovery efficiency was assumed for the baseline scenario based on experience of the author. Early recovery and a gas control scenario with additional infrastructure (geomembrane and booster pumps) were considered.

Despite mandatory early gas control (European Commission, 1999, 2014), in many European Member States, it is still common practice that gas wells are only installed after the entire landfill has reached its final height. Late gas control is therefore considered in the baseline European scenario. Standard recovery, early recovery and over-extraction were considered as additional scenarios.

For Africa, ‘no gas control’ was selected for the baseline scenarios with early recovery scenarios also included.

For South America and the Caribbean, it was assumed that gas control is through passive venting and passive flares for baseline and reduced organics scenarios. For early recovery and early recovery plus geomembrane placement (sometimes used to reduce water infiltration) scenarios gas recovery during waste placement was considered.

In North America, there is substantial variability in landfilling operational practices and selection of best management practices. These best management practices may entail early installation of a gas control system, frequent expansion and replacement of the gas control system, combination of different well types, redundant header pipe configurations, multiple blowers, frequent surface emissions monitoring, good cover material practices, limited working face dimensions, exposed geomembrane cap as interim cover in strategic areas and early placement of a final cover system. North American scenarios for three hypothetical landfills were evaluated:

- Scenario 1 – represents a typical landfill that implements nearly all best management practices in a rigorous manner.
- Scenario 2 – represents a typical landfill that implements some best management practices in a limited, casual manner.
- Scenario 3 – represents a typical landfill that implements few if any best management practices.

Over-extraction. Over-extraction entails that a lot more gas is extracted than is actually generated. This implies that air is introduced in or sucked into the waste body. Part of the degradation will therefore become aerobic and some methane might be oxidized to carbon dioxide, which will lower the methane to carbon dioxide ratio in the gas. Due to nitrogen gas intake, it will also reduce the absolute percentages of methane and carbon dioxide in the recovered gas. A mild degree of over-extraction can increase gas recovery efficiency or re-activate gas wells. In a more aggressive approach, it can be used to aerate landfills and can result in very high gas recovery rates (e.g. Cruz Osorio et al., 2021). In all cases, due to larger recovery flow rates, there will be less methane emission than with more traditional gas recovery (Berger and Lehner, 2022). In order not to overestimate its impact, this article assumes that the over-extraction recovery efficiencies are 30% during filling of the cell (years 2 and 3), 50% after temporary capping (years 4–6), 70% after permanent (semi-permeable) capping (years 7–20) and 90% from year 21 onwards. This implies that the first three stages are the same as early recovery. Consequently, in this study, over-extraction only impacts the GHG emission from year 21 onwards. Only low calorific flares can effectively burn gas of poor quality (Scharff and Jacobs, 2003). Over-extraction therefore has to be combined with low calorific flaring to destroy the residual methane in the gas. In countries where reduction of DOC disposed in landfills has been implemented some time ago (e.g. The Netherlands since 1996), the landfill gas quality has declined and gas-fuelled engines have been decommissioned. Over-extraction and low-calorific flaring are therefore suited to a DOC reduction policy.

Extended landfill gas recovery. In the United States, permits normally allow for cessation of gas collection and flare system 15 years after filling operations end, if less than 34 Mg per year of non-methane organic compounds are being collected (Wang 2020). In South American, scenarios a criterion of 250 m^3 CH_4 per hour was applied. In some European countries, active recovery and treatment can be replaced by passive methods when active recovery is ‘no longer technically feasible’ or when methane generation drops below 25 m^3 CH_4 per hour. The GHG emission resulting from the end stages of landfill gas generation can therefore be mitigated by extended landfill gas recovery system operation.

Microbial methane oxidation. Methane that is not recovered can be partially oxidized by microbes in a suitable capping or cover layer (e.g. an engineered soil). The IPCC recommends methane oxidation factors of 0.1 for managed landfills covered with methane oxidizing material and 0 for other situations. This approach

Table 4. Scenarios.

Scenarios continent	Region/country	Scenario	ID	Waste type and composition source	Gas control: Recovery % (realized in year after cell start)	Annual waste amount	Calculated DOC × DOCf	Calculated *k*	Climate	Source
Oceania	New Zealand	Baseline	NZ base	NZ Govt 2018	Early: 30% (y2), 50% (y4), 70% (y7), 90% (y17)	500.000	0.067	0.063	Boreal and temperate/wet	Kottek et al. (2006)
		Reduced organics	NZ red org	NZ Govt 2021: −50% organic waste	Early: 30% (y2), 50% (y4), 70% (y7), 90% (y17)	349.500	0.037	0.033	Boreal and temperate/wet	Kottek et al. (2006)
	Australia	Baseline	Aus base	Aus Govt 2020	Late: 70% (y31), 90% (y34)	500.000	0.086	0.093	Tropical/wet	Kottek et al. (2006)
		Early recovery	Aus early	Aus Govt 2020	Early: 30% (y2), 50% (y4), 70% (y7), 90% (y17)	500.000	0.086	0.093	Tropical/wet	Kottek et al. (2006)
		Early recovery plus reduced organics	Aus red org	Aus Govt 2019: −50% organic waste	Early: 30% (y2), 50% (y4), 70% (y7), 90% (y17)	333.250	0.044	0.047	Tropical/wet	Kottek et al. (2006)
Asia	South-Eastern Asia	Baseline	As 0	UTMM 2019; MHLGM 2012 and 2013	Standard: 50% (y4)	500.000	0.091	0.261	Tropical/wet	SAGE (2022)
		Reduced organics	As 1	Assumption: −20% food waste	Standard: 50% (y4)	460.000	0.089	0.249	Tropical/wet	SAGE (2022)
		Early recovery	As 2	UTMM 2019; MHLGM 2012 and 2013	Early: 30% (y2), 50% (y4)	500.000	0.091	0.261	Tropical/wet	SAGE (2022)
		Sealing and booster	As 3	UTMM 2019; MHLGM 2012 and 2013	Early: 30% (y2), 90% (y4)	500.000	0.091	0.261	Tropical/wet	SAGE (2022)
Europe	Europe	Baseline	EU 0/w	EC 1999	Late: 50% (y31)	500.000	0.061	0,081	Boreal and temperate/wet	SAGE (2022)
		Improved oxidation	EU 5/w	EC 1999 plus expert judgement	Late: 50% (y31)	500.000	0.061	0.081	Boreal and temperate/wet	SAGE (2022)
		Baseline	EU 0/d	EC 1999	Late: 50% (y31)	500.000	0.061	0.047	Boreal and temperate/dry	SAGE (2022)
		Reduced organics	EU 1/d	EC 2018; −71% MSW	Late: 50% (y31)	375.000	0.049	0.046	Boreal and temperate/dry	SAGE (2022)
		Red.org. plus standard recovery	EU 2/d	EC 1999 plus expert judgement	Standard: 50% (y4)	375.000	0.049	0.046	Boreal and temperate/dry	SAGE (2022)
		Red.org. plus early recovery	EU 3/d	EC 1999 plus expert judgement	Early: 30% (y2), 50% (y4), 70% (y7)	375.000	0.049	0.046	Boreal and temperate/dry	SAGE (2022)
		Red.org. plus over-extraction	EU 4/d	EC 1999 plus expert judgement	Early: 30% (y2), 50% (y4), 70% (y7), 90% (y21)	375.000	0.049	0.046	Boreal and temperate/dry	SAGE (2022)
Africa	Southern and Northern Africa	Baseline	Af 1	Expert judgement	None: 0%	500.000	0.098	0.075	Tropical/dry	SAGE (2022)
		Reduced organics	Af 1a	Assumption: −10% food waste	None: 0%	475.000	0.097	0.075	Tropical/dry	SAGE (2022)
		Early recovery	Af 1b	Expert judgement	Early: 30% (y2), 60% (y41)	500.000	0.098	0.075	Tropical/dry	SAGE (2022)
	Central Africa	Baseline	Af 2	Expert judgement	None: 0%	500.000	0.098	0.285	Tropical/wet	SAGE (2022)
		Reduced organics	Af 2a	Assumption: −10% food waste	None: 0%	475.000	0.097	0.285	Tropical/wet	SAGE (2022)
		Early recovery	Af 2b	Expert judgement	Early: 30% (y2), 60% (y41)	500.000	0.098	0.285	Tropical/wet	SAGE (2022)

(Continued)

Table 4. (Continued)

Scenarios continent	Region/country	Scenario	ID	Waste type and composition source	Gas control: Recovery % (realized in year after cell start)	Annual waste amount	Calculated DOC × DOCf	Calculated *k*	Climate	Source
South America and Caribbean		Baseline	SA 0/w	Kaza 2018	Passive: 20% (y3–y12)	500.000	0.092	0.243	Tropical/wet	SAGE (2022)
		Reduced organics	SA 1/w	Assumption: −15% food waste	Passive: 20% (y3–y12)	460.000	0.091	0.229	Tropical/wet	SAGE (2022)
		Early recovery	SA 2/w	Kaza 2018	Early: 30% (y2), 50% (y3), 70% (y5)	500.000	0.092	0.243	Tropical/wet	SAGE (2022)
		Early recovery plus sealing	SA 3/w	Kaza 2018	Early: 30% (y2), 50% (y3), 90% (y5)	500.000	0.092	0.243	Tropical/wet	SAGE (2022)
		Baseline	SA 0/d	Kaza 2018	Passive: 20% (y3–y12)	500.000	0.092	0.060	Tropical/dry	SAGE (2022)
		Reduced organics	SA 1/d	Assumption: −15% food waste	Passive: 20% (y3–y12)	460.000	0.091	0.058	Tropical/dry	SAGE (2022)
		Early recovery	SA 2/d	Kaza 2018	Early: 30% (y2), 50% (y3), 70% (y5)	500.000	0.092	0.060	Tropical/dry	SAGE (2022)
		Early recovery plus sealing	SA 3/d	Kaza 2018	Early: 30% (y2), 50% (y3), 90% (y5)	500.000	0.092	0.060	Tropical/dry	SAGE (2022)
North America		Nearly all BMP, baseline	NA 1 base	Expert judgement	Early: 50% (y2), 65% (y5), 90% (y31)	500.000	0.084	0.107	Boreal and temperate/wet	Expert judgement
		Nearly all BMP, reduced organics	NA 1a	Assumption: −43% organic wastes	Early: 50% (y2), 65% (y5), 90% (y31)	315.000	0.075	0.099	Boreal and temperate/wet	Expert judgement
		Nearly all BMP, early sealing	NA 1b	Expert judgement	Early: 50% (y2), 90% (y5)	500.000	0.084	0.107	Boreal and temperate/wet	Expert judgement
		Nearly all BMP, red. org. and early cap	NA 1a and b	Assumption: −43% organic wastes	Early: 50% (y2), 90% (y5)	315.000	0.075	0.099	Boreal and temperate/wet	Expert judgement
		Some BMP, baseline	NA 2 base	Expert judgement	Standard: 50% (y7), 90% (y31–60)	500.000	0.084	0.107	Boreal and temperate/wet	Expert judgement
		Some BMP, early recovery	NA 2a	Expert judgement	Early: 50% (y2), 65% (y7), 90% (y31–60)	500.000	0.084	0.107	Boreal and temperate/wet	Expert judgement
		Some BMP, extended recovery	NA 2b	Expert judgement	Standard: 50% (y7), 90% (y31–70)	500.000	0.084	0.107	Boreal and temperate/wet	Expert judgement
		Some BMP, early and extended rec.	NA 2a and b	Expert judgement	Early: 50% (y2), 65% (y7), 90% (y31–70)	500.000	0.084	0.107	Boreal and temperate/wet	Expert judgement
		Little BMP, baseline	NA 3	Expert judgement	Standard: 70% (y11), 90% (y31–50)	500.000	0.084	0.051	Boreal and temperate/dry	Expert judgement
		Little BMP, cell size reduction	NA 3a	Expert judgement	Standard: 70% (y6), 90% (y31–50)	500.000	0.084	0.051	Boreal and temperate/dry	Expert judgement
		Little BMP, early recovery	NA 3b	Expert judgement	Standard: 50% (y2), 70% (y11), 90% (y31–50)	500.000	0.084	0.051	Boreal and temperate/dry	Expert judgement
		Little BMP, cell size red. and early rec.	NA 3a and b	Expert judgement	Standard: 50% (y2), 70% (y6), 90% (y31–50)	500.000	0.084	0.051	Boreal and temperate/dry	Expert judgement

MSW: municipal solid waste; BMP: Best Management Practices; red.org: reduced organics; rec.: recovery; red.: reduction; NZ Govt 2018: New Zealand Government EPA (2018); NZ Govt 2021: New Zealand Government Climate Change Commission (2021); Aus Govt 2020: Australian Government (2020); Aus Govt 2019: Australian Government, Department of Climate, Energy and Water (2019); UTMM 2019: University of Technology Mara Malaysia (2019); MHLGM 2012 and 2013: Ministry of Housing and Local Government Malaysia (2012) and (2013); EC 1999: European Commission (1999); EC 2018: European Commission (2018).

Table 5. Parameters for the calculation of landfill gas to energy.

Aspect	Number	Unit
Methane content of landfill gas	50%	(50% because the IPCC modelling default is 50%)
Methane	0.714	kg per m^3
Energy content of methane	50	MJ per kg methane
Energy content of landfill gas	17.85	MJ per m^3 = 4.96 kWh per m^3
Availability of recovery	95%	
Availability of utilization	95%	
Total availability	7906	hours per year
Conversion of energy content	40%	to electricity replacing energy from the grid
	50%	to heat replacing thermal energy

IPCC: Intergovernmental Panel on Climate Change.

implies that oxidation in absolute numbers is higher when generation is higher and/or recovery is lower. In reality oxidation is a function of the soil porosity (enabling oxygen diffusion), temperature and moisture content. Oxidation is better expressed in terms of g CH_4 per m^2 per day. Literature studies (e.g. Huber-Humer 2008) have indicated that oxidation of 1 L CH_4 per m^2 per hour (17.1 g CH_4 per m^2 per day or 6.2 kg CH_4 per m^2 per year) in landfill covers seems realistic in moderate climates In a few European countries, active gas recovery and treatment can be replaced by passive recovery and microbial methane oxidation when the methane generation is below 25 m^3 CH_4 per hour or below 0.5 L CH_4 per m^2 per hour. Since for this study, landfill geometry was not considered, and the first criterion had to be applied. In a moderate climate, 50% oxidation (100% in summer, 0% in winter) is a conservative assumption.

Energy recovery. Energy recovery is a management approach that is promoted by regulators in many countries. Energy generated from landfill gas can substitute for energy produced by fossil fuel and thus result in a net GHG emission reduction. Energy recovery is possible in various ways. Electricity can be generated with, for example, gas engines or gas turbines. Hot water can be generated with boilers and heat exchangers in flares or gas engines. Clients for hot water are however often harder to find than clients for electricity or for direct gas use. It is also harder to distribute hot water than to connect to the electricity grid. In order not to underestimate the impact of electrical energy recovery, it was decided to take an optimistic approach in terms of the parameters used to calculate energy conversion (Table 5).

In Table 5, the most important parameter to calculate the climate impact of avoided fossil fuel for energy from landfill gas is not presented: the so-called grid emission factor. This is the number that indicates how much carbon dioxide is emitted for a kWh of electricity that is distributed through the electricity grid in a specific country or continent. The grid emission factor varies enormously throughout the world. Grid emissions factors by the Institute for Global Environmental Strategies (IGES, 2022) were applied. Alternatively more local sources were used. The source is mentioned in the calculation sheets (see repository: https://we.tl/t-2feXSc2lbN). The additional benefit of energy recovery in terms of avoided fossil fuel strongly depends on the energy mix that is avoided in a specific state or country. Recovered energy can only compensate for more than 10% of the climate impact of methane generation when it replaces energy from inefficient coal-fired power plants. Countries like Sweden, Iceland and New Zealand already have a significant proportion of renewable energy supply in the grid. In such countries, the climate benefit of landfill gas to energy is negligible. In other countries, the benefit will decline with progress towards a more sustainable energy mix.

The grid emission factor for the production of thermal energy (hot water) is less well described in literature. For pragmatic reasons, natural gas was chosen as the replacement fuel. Assuming an energy content of 44 MJ per kg, the combustible part mainly being methane, a combustion emission of 2.75 kg CO_2 per kg CH_4 and an energy conversion to heat of 90%, it can be calculated that the emission factor is 0.25 kg CO_2 per kW thermal energy generated. During transport and distribution of thermal energy, losses occur compared to local production. A conversion efficiency of 90% for natural gas can therefore be considered high.

Emerging landfill management technologies. Emerging landfill technologies, such as leachate recirculation and landfill aeration, have not been considered. The IPCC in 2019 has introduced MCFs for aerated landfills. The MCF is an overall factor that does not allow for calculations of management changes during the operational life of the landfill. It is not possible to model the impact of leachate recirculation or landfill aeration during different phases of operation, if the changes in reaction rate constants and DOCf are unknown. To date, insufficient data on this aspect are available to allow for its inclusion.

Uncertainties. Applying a multiphase instead of a single-phase model would have generated slightly different results. The single-phase model was however applied uniformly for all scenarios. Therefore, the comparative outcome between the scenarios is not affected. Uncertainties relating to parameters have not been included in this article. The IPCC default values and recommendations were followed where possible. If uncertainties would have been considered, they would have been based on uncertainties described in IPCC recommendations. They would therefore likely have a similar outcome for all scenarios. The more important factor is that both the model approach and the decision to not include uncertainties will not impact the comparative assessment of management approaches, and the intention of this article is to illustrate the relative importance of the different management choices.

Results and discussion

General

Scenario results are summarized in Table 6. All the underlying calculation spreadsheets for methane generation, recovery, oxidation, emission, energy recovery and comparison of results, including graphs, are available in a repository (https://we.tl/t-2feXSc2lbN). Methane generation over 100 years (Table 6) varies a lot between scenarios. This is due to different waste composition, different stages of DOC reduction already achieved and climate.

Reduced DOC content

Different regions on the planet will have different levels of regulatory obligations and ambitions to reduce DOC disposed in landfills (par. 2.4.1). This is reflected in the results as shown in Table 6. On continents where the ambition can be expected to be moderate, like Africa (Af1a, Af2a), South America (SA1/w, SA1/d) and Asia (As 1), the GHG emission reduction compared to the respective baseline scenarios varies from 5 to 10%. On continents where the reduction of landfilled DOC can be expected to be higher, like Europe (EU 1/d), North America (NA 1a) and Oceania (NZ red org, Aus red org), a GHG emission reduction varying between 40 and 72% can be achieved. The 89% reduction in the Australian reduced organics scenario is the combined impact of DOC reduction on top of early gas recovery. This shows that even when recovery is optimized, it is still possible to further reduce GHG emissions by reducing DOC in the landfilled waste. The results confirm that if the volume of DOC deposited in a landfill decreases, the GHG emissions are also reduced. As explained in the introduction, it is unfortunately not realistic to assume that the world can make big steps in reducing DOC input to its landfills in the next decade. In every single scenario (see repository: https://we.tl/t-2feXSc2lbN) after 30 or 40 years, the waste input, and consequently also the DOC input, stops completely. Yet after landfill closure, methane generation and emissions continue for many more decades in all scenarios. This implies that in order to maximize GHG emission reduction from landfills in the short term, more should be done than relying on reducing DOC input in landfills.

Landfill gas recovery

Different landfill standards on different continents resulted in not all of the five different landfill gas recovery approaches defined in this study being considered appropriate for each continent. This makes comparison between continents difficult. In scenarios within a continent, only a big step from no gas control to early recovery (Africa), from passive recovery to early recovery (South America) or from late recovery to early recovery (Australia) was considered. In the case of Africa, lower recovery efficiencies were selected than for South America and Australia. This explains why the GHG emission reduction of the African scenarios (AF 1b, Af 2b) is lower than the reduction calculated for South America (SA 2/w, SA 2/d) and Australia (Aus early). For Asia, early recovery (As 2) can be compared to standard recovery. This is a smaller step in terms of recovery effort and is reflected in a smaller additional GHG emission reduction. The scenarios As 3, SA 3/w and SA 3/d indicate that early construction of a surface sealing layer increases recovery efficiency. Operators should however account for replacement or repair of the sealing before final closure of the landfill as continued settlement of the waste is likely to damage the sealing system.

Four North American scenarios (NA 3, NA 3a, NA 3b and NA 3a and b) illustrate a stepwise increase of gas recovery. The baseline (NA 3) entails standard recovery. Reducing the cell size (NA 3a) means that standard recovery is started earlier and results in an additional GHG emission reduction. Introducing early recovery (NA 3b) results in a slightly higher reduction. The combination of cell size reduction and early recovery (NA 3a and b) provides a higher GHG emission reduction than the approaches individually. The European scenarios (EU 2/d, EU 3/d, EU 4/d) illustrate the impact of increasing the recovery effort after having reduced the amount of landfilled DOC (EU 1/d). The reduced DOC scenario EU 1/d assumes late recovery. Introducing standard recovery (EU 2/d) provides a 17% increase in GHG emission reduction compared to the late recovery. Early recovery (EU 3/d) and over-extraction (EU 4/d) provide 33 and 40% additional GHG emission reduction compared to EU 1/d. All these scenarios demonstrate that increasing the recovery effort and especially starting gas recovery early, when the gas generation is highest, increases the GHG emission reduction potential.

Over-extraction

Over-extraction is only considered in a European scenario (EU 4/d). A conservative approach was adopted. When compared to the baseline scenario (EU 0/d), over-extraction can achieve an 80% GHG emission reduction. It should however be noted that this reduction includes a reduction of DOC input according to European targets. When compared to the reduced DOC scenario (EU 1/d), over-extraction can accomplish an additional 40% GHG emission reduction. For this study, over-extraction did not deviate from early recovery until year 20 of the modelling period. With these conservative assumptions, from year 21 onwards over-extraction can nevertheless achieve a further 7% GHG emission reduction when compared to the early recovery scenario (EU 3/d).

Table 6. Scenario results.

Scenarios continent	Region/country	Scenario	ID	Methane generation (Gg.100y^{-1})	Methane recovery (Gg.100y^{-1})	Methane emission (Gg.100y^{-1})	Emission reduction due to management choice(s)	Avoided fossil fuel (GgCO$_2$ eq .100y^{-1})	Reduction due to energy recovery
Oceania	New Zealand	Baseline	NZ base	666	496	156			
		Reduced organics	NZ red org	239	191	43	72%		
	Australia	Baseline	Aus base	860	258	549			
		Early recovery	Aus early	860	600	238	57%		
		Early recovery plus reduced organics	Aus red org	284	220	59	89%		
Asia	South-Eastern Asia	Baseline	As 0	909	358	515			
		Reduced organics	As 1	825	328	464	10%		
		Early recovery	As 2	909	416	457	11%		
		Sealing and booster	As 3	909	645	257	50%		
Europe	Europe	Baseline	EU 0/w	607	118	477			
		Improved oxidation	EU 5/w	607	118	477	0.05%		
		Baseline	EU 0/d	596	161	419			
		Reduced organics	EU 1/d	362	99	253	40%		
		Red.org. plus standard recovery	EU 2/d	362	166	178	57%	158	1.6%
		Red.org. plus early recovery	EU 3/d	362	237	113	73%	242	2.4%
		Red.org. plus over-extraction	EU 4/d	362	268	85	80%	504	5.0%
Africa	Southern and Northern Africa	Baseline	Af 1	1062	–	1028			
		Reduced organics	Af 1a	1005	–	972	5%		
		Early recovery	Af 1b	1062	420	628	39%		
	Central Africa	baseline	Af 2	1066	–	1056			
		Reduced organics	Af 2a	1009	–	998	5%		
		early recovery	Af 2b	1066	351	711	33%		
South America and Caribbean		Baseline	SA 0/w	923	150	705			
		Reduced organics	SA 1/w	839	135	642	9%		
		Early recovery	SA 2/w	923	540	351	50%	1.108	4.3%
		Early recovery plus sealing	SA 3/w	923	646	256	64%	1.332	5.2%
		Baseline	SA 0/d	916	81	754			
		Reduced organics	SA 1/d	832	72	686	9%		
		Early recovery	SA 2/d	916	590	295	61%	1.225	4.8%
		Early recovery plus sealing	SA 3/d	916	750	152	80%	1.603	6.3%
North America		Nearly all BMP, baseline	NA 1 base	837	583	234			
		Nearly all BMP, reduced organics	NA 1a	474	331	131	44%		
		Nearly all BMP, early sealing	NA 1b	837	698	130	44%		
		Nearly all BMP, red.org. and early cap	NA 1a and b	474	395	74	68%		
		Some BMP, baseline	NA 2 base	837	422	392			
		Some BMP, early recovery	NA 2a	837	573	247	37%		
		Some BMP, extended recovery	NA 2b	837	428	386	1%		
		Some BMP, early and extended rec.	NA 2a and b	837	579	241	38%		
		Little BMP, baseline	NA 3	824	416	384			
		Little BMP, cell size reduction	NA 3a	824	476	322	16%		
		Little BMP, early recovery	NA 3b	824	498	302	21%		
		Little BMP, cell size red. and early rec.	NA 3a and b	824	515	282	27%		

BMP: Best Management Practices.

Extended landfill gas recovery

‘End of recovery’ criteria were not reached in any of the European scenarios. Extension of recovery was therefore not a consideration. Recovery was ended in the North American and South American scenarios according to the criteria. Two North American scenarios (NA 2b, NA 2a and b) considered extended recovery. The calculated contribution of extended recovery was 1%. Extended recovery occurs towards the end of the 100-year modelling period when methane generation has already decreased significantly. Therefore, the contribution to overall GHG emission reduction is relatively small.

Microbial methane oxidation

Microbial methane oxidation is only considered in a European scenario. Due to the European criteria for microbial methane oxidation as replacement for active recovery and treatment, it can only be considered towards the end of the end of the 100 year period, when methane generation has already reduced significantly. In the European scenarios calculated with parameters for a ‘temperate and boreal, dry climate’ (EU 0-4/d), methane generation was still above 25 m^3 CH_4 per hour at the end of the 100-year modelling period. Due to the higher degradation rate, in the European scenarios calculated with parameters for a ‘temperate and boreal, wet climate’ (EU 0/w, EU 5/w), methane generation was smaller than 25 m^3 CH_4 per hour from year 89 onwards. Microbial methane oxidation (EU 5/w) results in a 0.05% GHG emission reduction compared to the baseline scenario (EU 0/d). Most of the methane throughout the 100-year modelling period has been generated and emitted before microbial methane oxidation can be applied. Microbial methane oxidation will have a much bigger impact when it is applied a lot earlier in order to reduce the remaining emission during active recovery.

Energy recovery

Energy recovery was considered in the European and South American scenarios. In the European scenarios EU 2/d and EU 3/d, energy recovery (electricity only) can add another 1.6 to 2.4%, respectively, to the GHG emission reduction. Low calorific flares have been equipped with heat exchangers and can in combination with over-extraction (EU4/d) recover thermal energy. Theoretically, this could contribute another 3.3% GHG emission reduction to the over-extraction scenario (EU4/d). Energy recovery (electricity only) in the South American scenarios SA 2/w, SA 2/d, SA 3/w and SA 3/d provides an additional GHG emission reduction of 4.3, 5.2, 4.8 and 6.3%, respectively. None of the energy recovery scenarios provides a significant contribution to GHG emission reduction.

Conclusions and recommendations

The modelling per continent departs from different starting points and uses different parameters to reflect operational practices and trend expectations on those continents. Nevertheless, the results of the generic modelling exercise demonstrate similar trends. The results show that two aspects are the most significant for landfill methane emission reduction:

- Early gas recovery provides significant GHG emission reduction, even if it is considered to be carried out with a moderate gas recovery efficiency as for instance in the African scenarios. Early gas recovery entails gas recovery systems that are built up with increasing waste placement. This is especially important under warm and wet climate conditions with high waste degradation rates, where most of the landfill gas is generated shortly after disposal. Such an approach allows gas recovery to start during disposal. It is likely that the initial quality of the gas will be poor. Flaring or low calorific flaring could temporarily be the only methane oxidation options, until stable methanogenesis is established.
- Reduction of DOC input has a significant impact on landfill methane emissions. The Asian, African and South American scenarios however indicate that, if it is limited to food waste, the impact is also limited. The Oceanian, European and North American scenarios demonstrate that more rigorous reduction of DOC to landfill (including yard waste and especially article and cardboard containing wastes) are necessary to obtain a significant impact.

This article confirms that the IPCC (2022) recommended methane mitigation measures for the waste management sector (reduction of organic waste to landfill) can be effective. But, due to the lengthy preparation time and cost required to achieve this, it is not a measure that is effective immediately. Even if complete deviation of organic waste from landfills could be realized tomorrow, the waste that has already been disposed will continue to generate significant amounts of methane for decades. Reduction of DOC alone will not enable a significant contribution of the waste management sector to the 2030 targets of the Global Methane Pledge. Landfill gas recovery entails basic, standardized, technology that can be deployed swiftly and at moderate cost. The combination of rigorous reduction of DOC and early gas recovery and/or over-extraction can have an impact quickly and has the largest landfill methane mitigation potential. In order for nations to obtain maximum benefit, it is recommended that, in parallel with organic waste to landfill reduction, they should make more efforts to stimulate early landfill methane recovery and destruction. In addition, it is recommended that the potential of over-extraction and low calorific flaring be further investigated and documented in peer-reviewed articles.

Improvement of passive oxidation (when active recovery becomes difficult) has a negligible impact on the overall methane emissions from a landfill. This conclusion is however based on countries that have regulations in place that do not allow passive treatment as long as it is ‘technically feasible’ to operate active gas recovery. Passive oxidation may be more effective when applied in parallel with active recovery.

The contribution of energy recovery is limited. Higher GHG emission reduction from landfills is possible without energy recovery by means of more aggressive gas recovery and destruction of methane in low calorific flares. Energy recovery can however continue to be an economic consideration.

For maximum GHG mitigation, it is recommended that regulators shift their focus from ‘energy recovery from landfill gas’ to ‘maximum achievable methane destruction efficiency’.

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