40 YEARS AFTER LOSCOE, LANDFILLS HAVE CHANGED. CAN WE STILL PREDICT THEIR BEHAVIOUR?

R. Gregory [1], S. Davies [2], M. Holden [3], M. Moran [4]

[1] Gregory Environmental Consulting Ltd, 4A Middle Lane, Nether Broughton LE14 3HD UK
[2] WRc Ltd, Frankland Road, Blagrove, Swindon, Wiltshire, SN5 8YF UK
[3] Holden Environmental Ltd, 19 Burwood Drive, Queensbury, Bradford BD13 2FJ UK
[4] Egniol Consulting Ltd, Unit 7, Llys Onnen, Ffordd y Llyn, Parc Menai, Bangor LL57 4DF Wales

ABSTRACT: Farquhar and Rovers (1973) demonstrated the biochemistry of landfill gas production, but the Loscoe landfill gas migration incident of 1986 led to a better understanding of the behaviour of landfill gas in the environment. Early empirical models relied upon enzymatic hydrolysis, the rate determining step in waste degradation, to control the rate of landfill gas generation, and this has not changed to this day. With the current focus on a circular economy, and the disappearance of landfills as a primary waste disposal route, we are seeing the loss of support in an industry that is past its peak, but has the potential to be both a useful disposal route, and a significant hazard if left unattended.

Landfill will always be needed. Not just for materials that can't go anywhere else, or used in an emergency (such as BSE in the 1990s, or Foot and Mouth disease in the 2000s). Landfill is, and will remain, a part of any national or regional waste management strategy for the foreseeable future. The inputs will continue to change in terms of quantity and composition, the economics are challenging and a core landfill provision need to be commercially viable to service the need and to manage the legacy risks.

Total elimination of the source term hazard posed by landfills is not practicable. Appropriate risk assessment and management of those risks is the only viable strategy. Risk assessing landfills is difficult and the tools have not kept pace with societal changes. Landfilled residual wastes have changed over time and are highly heterogeneous and poorly characterised. Measurement and monitoring is still not easy to do. Modelling is only as successful as the quality of the inputs to the models, and the effort applied to validate models. The empirical models that do exist and have been successfully used in the past (IPCC, GasSim, and LandGEM) need to be brought up to date and used to address the problems of today (and tomorrow) if we are not to repeat the mistakes of the past. Default data is not good enough.

Regulation cannot be based on achieving a so-called collection efficiency either, as this is usually based on the difference between two model parameters. Practical full site emissions measurements to determine collection efficiency is expensive. A focus on climate change policy as an avenue for future LFG regulation may be appropriate. Regulating on the basis of modelled or measured human health or odour impacts does not assist the landfill operator to understand the cause and solutions which are applicable. If abatement of methane emissions is to be the reason to continue landfilling, then we need methods of quantifying emissions that satisfy the level of scrutiny required.

Keywords: landfill gas, waste degradation, gas generation, residual waste, fines, hydrogen sulphide, methane, VOCs, artificial intelligence, regulation, regulators, operators, training.

1. INTRODUCTION

In 1986, a deep low-pressure event (40mbar or 4kPa pressure drop) led to lateral migration of landfill gas from a recently capped but unlined landfill at Loscoe, Derbyshire. No 51 Clarke Avenue in Loscoe was totally destroyed when the pilot light of the boiler flashed up, after landfill gas had accumulated below their property (Figure 1; Aitkenhead and Williams, 1986; Williams and Aitkenhead, 1991). Fortunately, the three people in the house survived this explosion. 40 years on from the Loscoe incident, this paper looks at what we have learned (or forgotten) since Loscoe, what has changed in terms of waste composition and degradability, and whether we have the basic biochemical and physical understanding of how new, residual waste landfills will behave in the future, in the UK and elsewhere.

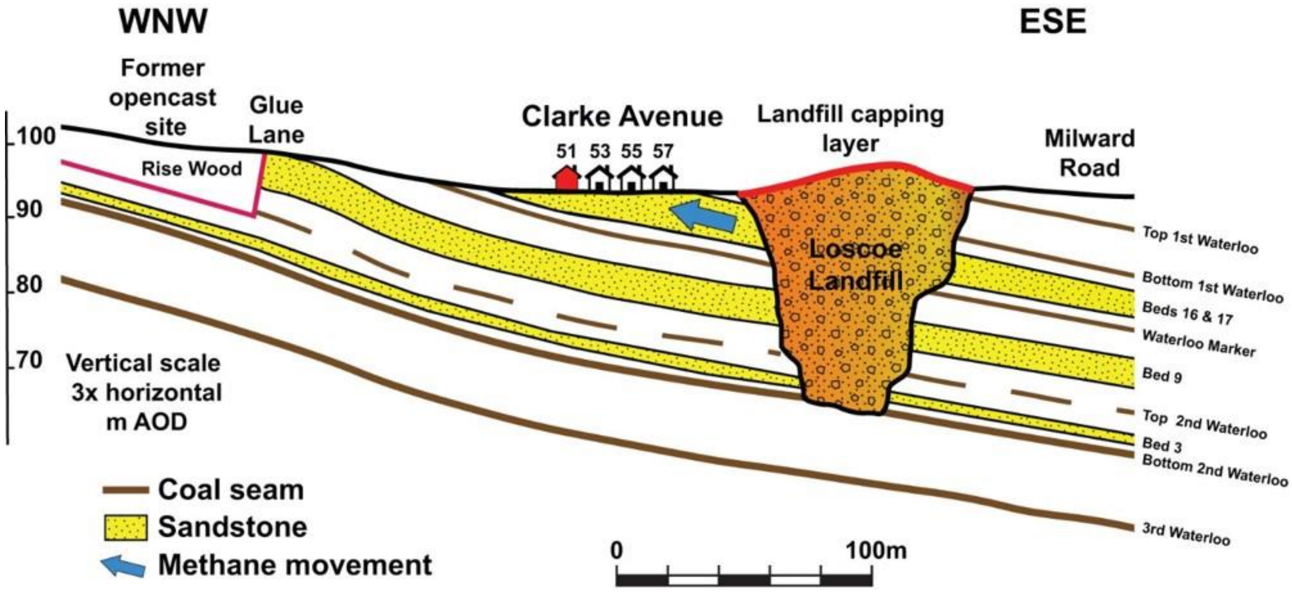

Figure 1. Geological Cross-Section through the Loscoe Landfill (redrawn from Williams and Aitkenhead, 1991).

Loscoe was a turning point in the regulation of landfill gas in the UK. There were once many thousands of small unlined landfills accepting municipal wastes across the UK. There are over 21,000 landfills in the UK, but only 1,841 of these are currently permitted under the Environmental Permitting Regulations 2016 (EPR). 1,257 of these permitted sites were previously licensed and regulated under the Waste Management Licensing Regulations 1994 (WML). Of the 19,612 unpermitted English landfills 2,195 (11%) are in public control and 3,988 (20%) in private control. The remaining 13,429 (69%) are currently of unknown ownership/control. Many sites closed rather than move into the PPC permitting regime from 2003 onwards (Brown et al, 2918).

Waste management guidance in the UK has been in place since the mid-1980s. Waste Management Paper 26, Landfilling Wastes, was first published in 1986 (HMSO, 1986), at which time there were estimated to be over 4000 licenced landfills. Regulation was under the Control of Pollution Act (1974). There were both containment sites and attenuate and disperse sites in operation. Most efforts (in terms of the amount of guidance published) were focussed on leachate management, as sites were predominantly small and the volumes of landfill gas likely to be generated were recommended either to be vented to atmosphere or flared. Capping a landfill to reduce leachate production was a recommendation but this had knock on effects on landfill gas generation, and the Loscoe lateral migration incident was a direct result of the local authority capping the landfill without catering for landfill gas management and without a conceptual site model of the site, or what the quantitative risks were of capping the site. Waste Management Paper 27 (HMSO, 1989), specifically on landfill gas, followed after the Loscoe incident in 1989, with a second edition in 1991.

Farquhar and Rovers (1973) demonstrated the biochemistry of landfill gas production, but the Loscoe incident led to a better understanding of the behaviour of landfill gas in the environment. Early empirical models of landfill gas production clearly relied upon enzymatic hydrolysis, the rate determining step in waste degradation, to control the rate of landfill gas generation, and this assumption has not changed to this day. Most focus was on the lateral migration risk from actively gassing unlined landfills. Passive venting on the site boundary was encouraged, followed by pumped perimeter gas control schemes.

The idea that gas from the entire site could be utilised in some way was only investigated in the second half of the 1980s, with the Liverpool Garden Festival Site one of the pioneers in that respect. Shanks and McEwan were also leaders in gas utilisation at the time, using landfill gas from former London Brick clay quarries in the Marston Vale.

2. MODELLING THE CHANGING ROLE OF LANDFILL

Always towards the bottom of the waste hierarchy, landfill has moved from the traditional method of engineered waste disposal for mixed degradable wastes to a managed facility for the final disposal of residual wastes from materials processing. Inevitably the types of materials sent to landfill are therefore changing, both in chemical composition and in their reactivity.

The risk of such changes in the materials sent to landfill impacting on risk assessments should not be underestimated. If you start with components of a mixed waste and recover the clean components for reuse, diverting these from landfill, you are inevitably concentrating the contaminants into the residual fraction. This is analogous to the two fractions which are produced during reverse osmosis of leachate. While RO produces a very high volume of clean liquid, there is a concentrated liquor which contains all the contaminants, at much higher concentrations than from the original leachate fraction. We are observing this in the residual wastes being sent to landfill, while expecting the standard risk assessments to be representative.

Taking GasSim as an example from the UK:

- The waste streams and waste degradation rates initially modelled in GasSim v1.0 (released circa 2003) were wastes suitable for the period 1980 – 2000. The compositions came from a ETSU research report of 1990 (Manley et al., 1990), BJW, Wilson DC, and Tillotson HS (1990). National Assessment of Landfill Gas Production. ETSU Report B1192.) and the waste degradation rates from an Emcon Associates paper by John Pacey in the Bournemouth Conference of 1990 (Pacey and Augenstein, 1990). For GasSim 2, waste compositions for the devolved administrations came from work on the National Household Waste Analysis Programme in the mid-1990s (Warren Spring Laboratory, 1994a; 1994b; NETCEN, 1995). Industrial and Commercial waste streams were provided for a number of default industries and activities (Golder Associates, 2005). Remember at this point in time the European Waste Catalogue (EWC) codes were not in use in the UK.
- Assumptions on waste diversion from the municipal solid waste stream were made in GasSim that carbon was diverted from waste streams at equal rates across all waste components. This did not happen in reality. The waste industry diverted waste from landfill that was easiest to divert first. So metals, green garden waste and both commercial and household packaging were first to be diverted. Textiles followed, and as alternative treatments for organic waste came on stream, like Anaerobic Digestion, organic wastes were diverted from landfill, but again these were more likely to have been from commercial rather than household wastes.

As metals were diverted from landfill, the first signs of unexpected consequences were seen. Hydrogen sulphide concentrations began to rise in landfills from the mid-2000s onwards (Stalleicken and Slack,

2010) This was as a result of the removal of zero valent metals for recycling and the buffering effect of iron and similar metals in the landfill. Sulphate reducing bacteria (SRBs) are tough and will suppress methanogens as they compete for substrate within the landfill. There is a fine balance between the availability of iron as a sink to produce iron sulphide, or the production of hydrogen sulphide if the iron fraction is absent. There are a number of other processes which can exacerbate hydrogen sulphide generation in landfills but the absence of iron is potentially the most important.

More recently, material recovery can have quite a significant impact on the waste streams landfilled. Fines, now classified under the category 19 12 12 “other wastes (including mixtures of materials) from mechanical treatment of wastes other than those mentioned in 19 12 11” are a significant fraction of the residual wastes now being landfilled. These materials may often have a low carbon content (LOI ≤10%), but their fine-grained composition means that gas generation, and overall reactivity generally, is enhanced compared to the more bulky nature of unsorted wastes. Figures 2 – 4 show this type of waste being produced, delivered to a landfill, and finally seen in situ. GasSim and other internationally validated models do not have a waste stream default representative of these wastes.

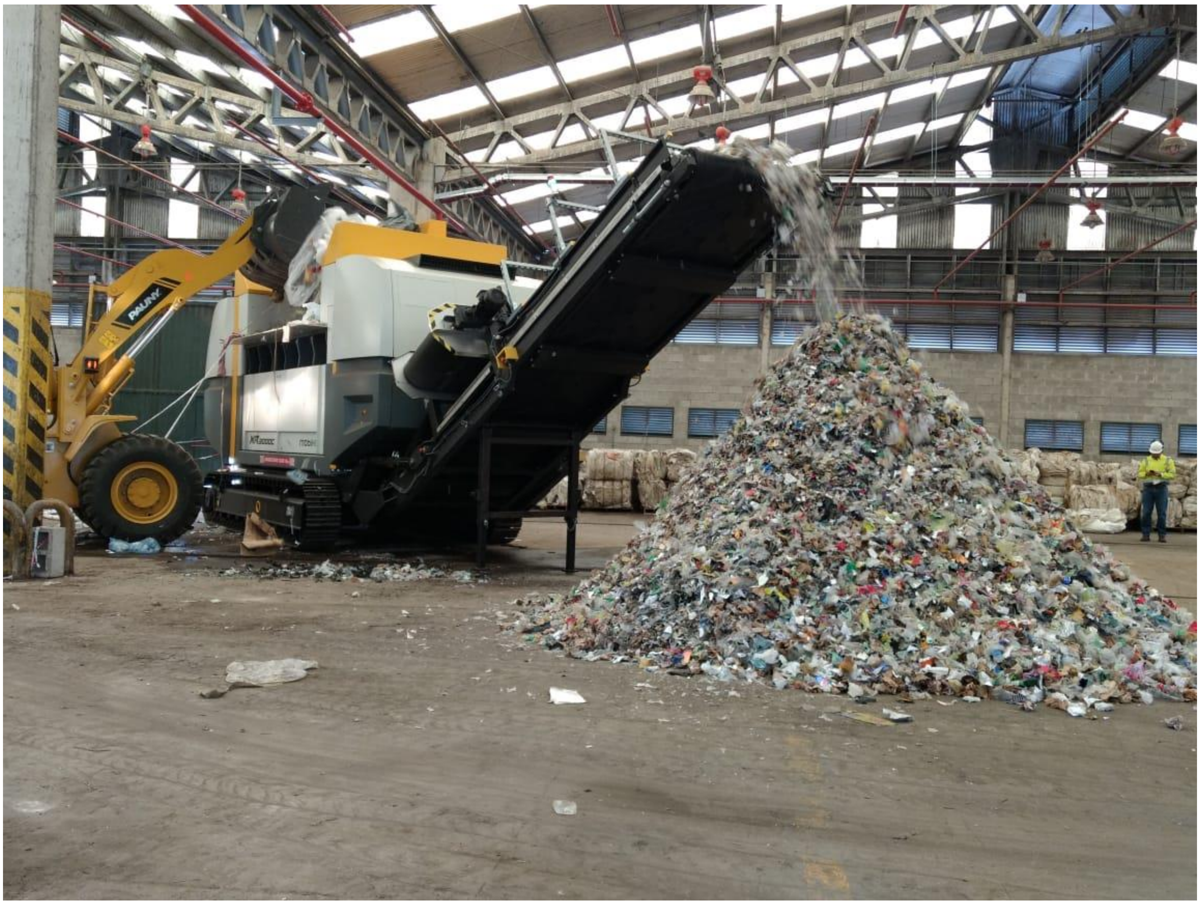

Figure 2. A simple waste shredding operation which produces fines as a residual waste material after sorting.

Figure 3. Fines being accepted at a landfill weighbriidge.

Figure 4.Fines emplaced in the landfill environment.

As more and more commercial and industrial treated waste streams enter the landfilling environment, other gases may become more prevalent in the landfill gas composition. Hydrogen is one example, and there is evidence of this from industrial and frag wastes, for example (Leeding et al, 2014). High non-methane VOC concentrations can also be observed in some landfill gas samples, and VOCs interfere with the hand-held analysers that many of us use on site. It can be quite common to observe over-high methane concentrations, zero balance gas concentrations, and total gas concentrations well over 110% when using hand held analysers if VOCs or hydrogen concentrations are high in the landfill gas. Only laboratory samples of landfill gas will give accurate interpretations in such a situation.

As a result, landfill gas models can struggle to represent the wastes which are regularly being landfilled today and into the future. Risk assessing landfills is difficult and the tools have not kept pace with societal changes. Landfilled residual wastes have changed over time and remain highly heterogeneous and poorly characterised. Measurement and monitoring is still not easy to do. Modelling is only as successful as the quality of the inputs and the effort applied to validate models. The models that do exist and have been successful in the past (IPCC, GasSim, and LandGEM) need to be brought up to date and used to address the problems of today (and tomorrow) if we are not to repeat the mistakes of the past. This paper is intended to be model agnostic, because at a practical, all empirical LFG models tend to use a similar core set of algorithms. There are countless papers in the academic press which have used default data values to compare models, and which arrive at unsafe conclusions, because not only do default data vary from model to model, but the default parameters used in the algorithms can vary, with different assumptions of degradable carbon content and waste degradation rate (amongst others). For example, LandGEM 3.1 now issues clear caveats on the use of certain default modes in the model which are intended for US regulatory purposes but will over-estimate landfill gas generation and emissions (Krause and Thorneloe, 2024).

3. EFFECTS OF POLICIES ON PRACTICAL RISK MANAGEMENT

A significant development in the management of landfill gas in the UK was the onset of Pollution Prevention and Control (PPC) Permitting in 2002 (Pollution Prevention and Control (PPC) Permitting Regulations, 2000). Landfill sites were permitted in seven tranches over three and a half years and all sites that went into permitting had to have three risk assessments: a landfill gas risk assessment (LFGRA), a hydrogeological risk assessment (HRA), and a slope stability risk assessment (SSRA). The LFGRAs were supported by the GasSim model (Golder Associates, 2005). This was developed as an applied research project for the Environment Agency in the late 1990s (Gregory et al., 1997). The Health and Environmental Effects of Landfill Gas (HELGA) model used the waste composition and waste degradability to assess the environmental impacts from various emission vectors from a landfill. This model was commercialised as GasSim v1.0 in 2003. To align GasSim with a consistent approach used across industry for air quality, a quick fix screening tool was added to GasSim v1.5 by 2004.

Realistically, all landfill gas models use a similar approach, degrading the available cellulose in different waste fractions, sometimes by different waste degradation rates, but always using empirical waste degradation rates which appear to be determined primarily by climate/moisture content of the waste.

A large applied research study for the Environment Agency funded by Landfill Tax Credits on methane emissions in the operational phase of landfills helped us to understand how quickly emissions could be released from landfills (Barry et al., 2004) development of GasSim 2, which allowed a more detailed cellular filling profile to be incorporated into the LFGRA, along with temporary capping, permanent capping, and surcharging. It was now (by about 2007) possible to simulate the filling regime much more accurately than before. Along with this came the incorporation of a basic version of the atmospheric dispersion model AERMOD into the model. This was done to align the LFGRA approach with that used by other industries. Furthermore, waste diversion targets had been introduced in 2005 as part of the EU

Landfill Directive requirements and local authority recycling targets set up under Waste and Emissions Trading (WET) Act 2003. GasSim's default waste compositions were adapted to follow the waste diversion targets, and GasSim 2 was released in 2007 (Gregory and Browell, 2011).

Throughout the 1990s, landfill gas utilisation projects were encouraged by the Non-Fossil Fuel Obligation (NFFO) and the number of sites installing full site gas collection and control, with electrical energy as the product of gas utilisation, increased. Subsequently the Renewables Obligation (RO) has had a similar role to incentivise landfill gas utilisation, but that incentive expires for most UK landfills in March 2027. The combination of financial and regulatory incentivisation to collect, control, and exploit LFG is a potent tool for emissions management.

Before waste diversion from landfill, and during the early stages of waste degradation, gas to energy generation in a landfill can appear seemingly endless, as the gas curve is on the rise. The types of degradable waste sent to landfill, and the subsequent revenue stream from power generation made it worthwhile as an operator. There was little concern about residual emissions because we believed we were efficient at collecting landfill gas. As the years have progressed, gas generation has changed due to those very waste inputs changing (there are many references which can be followed up in the additional references section of this paper), but the field balancing technique to control the generation however, have not kept pace with waste compositional changes.

To balance a gas field to flare or engine, i.e. to recover the same amount of gas that is being generated, year on year, there are significant differences between an operational landfill prior to waste diversion, an operational landfill taking residual wastes now, and an aftercare site. Each requires a different approach to capture the gas, and this skill is being lost because the training and understanding of the chemical and biological changes in landfill as the wastes follow policy and regulatory changes, is no longer a priority. It is said that there are technicians on landfill sites that make gas balancing look easy, and their gas fields never crash. This is because they understand the site and have been trained to understand their equipment; they don't just collect data but they understand it.

However, there are still aspects of gas balancing that are not adopted by all operators and the observation of flow is one of them. If 60% methane quality is observed on an old site, for example, inexperienced managers and regulators start to believe this is recoverable, when indeed it is most probably stagnant with no flow at all. Completing the understanding with basic science, gas balance data and flow data also teaches the technicians where the gas is coming from, and which are the gas wells that are performing well, or equally will have major influence should a low pressure weather front hit, and a change in barometric pressure influences the ease with which the gas is given up.

Similarly, the last line of defence against lateral migration, the closest gas wells to the site perimeter, should always be understood and controlled to ensure that migration is prevented. This is part of this learning curve that we should have been teaching all these years, but have we?

As the gas generation rate slows, and the site is on the back end of the gas curve, then less adjustment of the site is needed, because it takes longer for balancing activities to affect the area of influence around the gas well. There are other influences on gas recovery, such as infrastructure maintenance, leachate management, and external meteorological forces, and a holistic approach is required to ensure that active gas recovery is accomplished, but if we don't even get the basics right then how are we to manage the end result?   If there is a engine on site and power generation is a priority, then it is common to stress the gas field to get more gas. In the good old days when waste composition was cellulose rich, gas was seemingly limitless. Problems arise if the operator measures the performance of the gas field against the defaults in the risk assessment model, since this is also the indicator that the regulator expects to measure against. The gas generated today is not a slow release. High surface area residual waste materials have fast gas production rates and the gas can be gone just as quickly. What would take 6 months historically for gas generation to start (Barry et al., 2004) is now taking weeks, meaning that operators need to construct extraction systems earlier in the process of waste placement to negate the potential odour issues caused by these waste streams, and harness the landfill gas more efficiently than before. These waste streams are not as well understood as the traditional wastes which were evaluated in depth in the

1980s and 1990s, and this knowledge is needed to produce reliable risk assessments and to be able to demonstrate best landfill gas management practice.

GasSim and other models can be used to represent current waste types, with a little effort, but the way this is done is more as a curve fitting exercise, using forecast power generation outputs to calibrate the models, rather than using tested waste compositions which have appropriate waste degradation rates from the start. This can lead to misunderstanding of overall gas collection efficiency and potentially under-estimating environmental impacts on air quality.

4. LOOKING TO THE FUTURE

4.1 Retention of knowledge

Those of us who were at the forefront of developments in the 1990s, and are now nearing retirement age would hope the knowledge we have gained through our years in the industry is retained in the industry, but that is not necessarily guaranteed. Landfills are, in some jurisdictions at least, considered politically non-existent. Many Universities have quietly dropped landfilling from waste management higher degrees in favour of circular economy courses. As an industry, we pretend that landfills no longer exist, but they remain a necessary part of the circular economy. While some of the older literature and ways of managing landfills needs updating, and it has a role in the understanding of the historical impact of changing waste streams, it is not todays answer due to the changes in waste stream diversion, recycling, and the circular economy. That is why we need to look at what is happening now with the waste streams sent to landfill. Do we have the training and knowledge transfer correct? Do we have the technology in place to understand the changes?

We have stood still over the last decade and a half and reaped the financial rewards from landfill gas to energy revenue. While policy changes have sought a world where landfill would disappear, most practitioners would agree that landfill is never going to disappear. It will change, of course, as it is responsive to the society of today, and even though we look at recycling and re-use and renew, we are still a society of consumption. Landfill is the only engineered facility that can cope with continued societal consumption and doesn't require a shutdown. Landfills can take just about everything you throw at it, but the changing and evolving biochemistry and kinetics needs to be understood to be appropriately managed. Significant research is now required to assist these residual waste landfills, the waste streams that are directed to final disposal, and their environmental impacts. Landfill needs to come to the fore and take a stronger role in the end game of waste, rather than hide in the shadows.

At a practical level, we urgently need to:

- Develop a new framework for assessing all regulated, unregulated and closed landfills, combining best practice from landfill gas management, and contaminated land risk assessment.
- Design new tools and models that can cope with data uncertainty and mixed waste profiles from residual waste streams that did not exist ten years ago.
- Fund targeted site investigations, with standardised methods, so that risk profiles can be meaningfully compared across regions.
- Train the next generation of consultants, engineers, and regulators to understand how landfill sites really work — before the current generation retires.

What is required first is a pooling of compositional analysis data from industry, which we know should be undertaken for waste classification purposes, and testing such as the BMP testing of waste streams to ascertain total landfill gas yield from these new residual waste streams we are now managing. The interactions between these waste streams needs to be understood, so that the kinetics as well as the redox potential and biochemistry of the wastes can be correctly represented in future landfill gas risk assessment models.

The regulator expects LFGRAs to be realistic, but has not provided guidance to date on how to represent any of these newer industrial and commercial waste streams and residual waste streams. It is time for everyone to work together on this challenge.

4.2 The Case for AI in Landfill Management

Artificial Intelligence is no longer the future. In many parts of the waste sector — particularly energy from waste and automated materials recovery — AI is already embedded in routine operations. Machine learning models optimise combustion conditions, robotic systems identify and sort materials on the conveyor, and predictive analytics guide plant performance. But in the world of landfill? We are barely scratching the surface.

This is a missed opportunity. The landfill sector generates vast quantities of structured and semi-structured data, often collected at great cost and effort. Gas monitoring, leachate quality, borehole dips, waste acceptance records, settlement surveys, weather logs — they accumulate year after year, site after site. Yet, for the most part, these datasets sit in static spreadsheets, siloed monitoring databases, or hardcopy folders. Analysis is reactive, narrow, and often limited to what can be achieved manually within reporting deadlines.

AI can change our vision of risk management entirely. With the right tools, we can identify patterns across time and across sites, flag anomalies before they become issues, model complex interactions between variables (like barometric pressure and methane migration), and even estimate unmonitored conditions based on correlated data. Leachate exceedances, gas balance instability, migration risks — these are problems that AI can help detect faster and with more confidence than traditional manual review.

The application of AI is compelling. In landfill gas, AI would be able to detect subtle flow drops, assess field balancing efficiency, and predict output curves — even where data is patchy or site infrastructure is ageing. In leachate management, AI can correlate weather, pumping rates, and chemical trends to predict potential compliance failures before they happen. In waste acceptance, machine learning models can flag suspect consignments based on composition history, origin, or deviation from norms.

This isn't hypothetical — these techniques are already being used in adjacent sectors, such as wastewater treatment, EfW, and even agriculture. The technology exists. The barrier is cultural, structural, and ultimately financial. The landfill sector has historically lagged in digital investment, and as a result, we are under-utilising the very data we generate.

This is not a pitch for one product or platform. It's a broader point: AI belongs in the landfill environment. Whether for compliance, performance optimisation, or strategic planning, the tools are now available — and they are only going to get more powerful. As the industry ages and tacit expertise begins to retire out, AI also offers a way to embed operational knowledge into tools that can support the next generation of landfill managers.

4.3 Supporting the Regulator of the Future

AI doesn't just offer benefits for operators — it can play a critical role in supporting the next generation of environmental regulators. As experienced landfill officers and technical specialists retire, agencies are facing a knowledge gap that will take years to close. Many of the new professionals joining the regulatory system have strong scientific or compliance backgrounds but limited real-world experience with landfill gas behaviour, leachate chemistry, or historical site infrastructure. AI can help bridge that gap.

With access to large datasets across sites and years, AI tools can:

- Highlight early warning signs of underperformance or pollution risk
- Benchmark sites against similar landfills, enabling smarter prioritisation of audits
- Translate complex monitoring data into simple dashboards or risk summaries

- Identify outlier values, anomalous patterns, or recurring permit breaches

AI can learn from historic case outcomes to recommend proportionate regulatory responses, but this isn't about replacing skilled regulators — it's about giving them the tools to ask better questions, faster. In a landscape where staff are stretched and data volumes are overwhelming, AI is the assistant every regulator deserves.

A narrow focus on climate change policy as an avenue for future LFG regulation may be the way to get financial support to invest in these future needs, but it needs to be appropriate. A knee jerk reaction to modelled or measured human health or odour impact is easy for a regulator to demonstrate but does not assist the landfill operator to understand the cause and solutions which are applicable. This is treating the symptom and not the cause. If abatement of methane emissions is to be the vehicle to continue investment, then we need methods of quantifying emissions that satisfy the level of scrutiny required.

DISCLAIMER

The authors of this paper are grateful to their employers for the opportunity to express their personal experiences. The opinions given in this paper are those of the individual authors and not necessarily their employers or clients.

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