Supplemental Material: Solid Waste Sector Methane Mitigation Technical Brief Series

Phases of Landfill Decomposition

There are four phases of landfill decomposition. Each phase has a different composition of gas produced (see Figure 1).

Phase I: The bacteria break up longer molecular chains in organic waste. The primary gas produced 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 II: In this phase, the landfill becomes highly acidic, as bacteria convert compounds under limited oxygen availability into acids and alcohols. As the acids mix with the moisture present in the landfill, they cause certain nutrients to dissolve, making nitrogen and phosphorus available to the increasingly diverse species of bacteria in the landfill. Carbon dioxide and hydrogen are the gaseous byproducts of these processes.

Phase III: The bacteria form acetate, an organic acid. This causes the landfill to become a more neutral environment in which methanogenic (i.e., methane-producing) bacteria begin to establish themselves. Acid-producing bacteria create compounds for the methanogenic bacteria to consume. Methanogenic bacteria consume the carbon dioxide and acetate.

Phase IV: The composition and production rates of landfill gas remain relatively constant. Landfill gas production is stable and usually contains approximately 45 to 60 percent methane by volume, 40 to 60 percent carbon dioxide, and 2 to 9 percent other gases, such as sulfides.

The following factors affect methane production in landfills:

- **Waste Composition:** Only organic waste generates methane. The type of organic waste affects the rate at which the waste decomposes, thus affecting the rate of methane generation.
- **Age of Waste:** The age of waste determines the anaerobic (i.e., without oxygen) condition of the waste, and hence affects the methane production.
- **Waste-in-place:** Higher tonnage of organic waste in a landfill will generate more methane.

- **Meteorological Conditions:** Atmospheric factors, such as rain, humidity, temperature, and atmospheric pressure, affect the rate of decomposition, and therefore the production of methane.
- **Type of Landfill Cover:** The cover type (daily, intermediate, or final) affects the level of moisture infiltration and applied vacuum to the gas collection system.

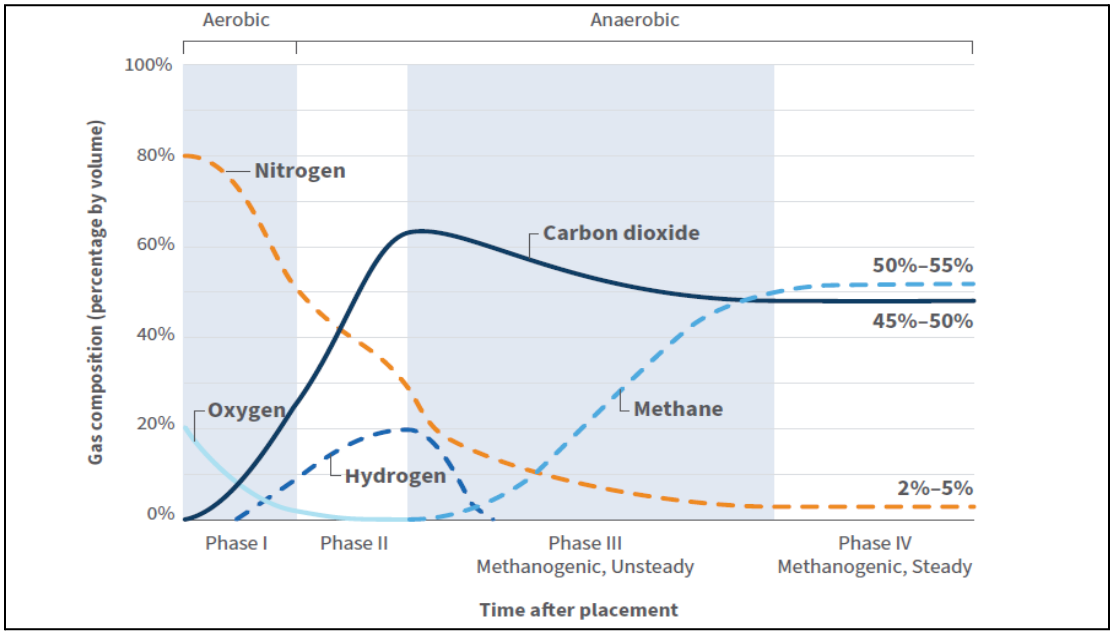

Figure 1: Gas Composition Produced in Different Phases of Solid Waste Decomposition
Source: "Basic Information of Landfill Gas," EPA.

Land disposal sites can be categorized into unmanaged and managed sites. As the name suggests, **unmanaged** land disposal sites are usually unmanaged and unregulated. They may have hazardous waste and are breeding grounds for pathogens. These sites pose public health and safety risks. There are two broad categories of unmanaged land disposal sites: **open dump sites**, where solid waste is uncovered, unmanaged, and not compacted, as well as sometimes burned (releasing hazardous gases); and **controlled dump sites**, where the solid waste is compacted and covered daily, but lacks environmental control systems such as liners, leachate collection and treatment, or gas collection and flare systems. **Managed** land disposal sites are designed, operated, and monitored for environmental compliance and public safety. These sites do not accept hazardous waste. Two types of landfills are usually considered managed: **sanitary landfills**, also known as engineered landfills, which are managed with regulatory oversight and environmental control systems; and **processed waste landfills**, which are similar to sanitary landfills but only accept processed waste (i.e., waste that has been treated or recyclable and organic material removed).

Key Considerations And Potential Interventions

The table below summarizes key considerations and potential interventions mapped to pre-land disposal site strategies and land disposal site strategies, as outlined in a 2022 RMI report.[1]

Table 1. Key Considerations and Potential Interventions

Category	Strategy	Key Considerations	Potential Interventions
Pre-land disposal site strategies	Food waste prevention	**Developed Countries** • Typically happens at households, catering, and retail levels. • Drivers include aversions to selling or buying imperfect foods (cosmetic standards), low consumer prices, and adherence to best-before dates.	• Individual behavior changes: Better food planning, preparation, preservation, and storage. • Large food retailers: Better aligning their inventories with consumer demand, developing strategies to utilize imperfect or surplus produce, educating consumers on waste reduction strategies, developing easy-to-understand product labels. • Corporations: Evolving their business models to incorporate food waste reduction initiatives.
		Developing Countries • Food waste happens primarily at the production, storage, and distribution levels. • High- and middle-income households show similar food waste behavior as in developed countries.	• Improving the cold chain management of perishable foods. • Improving packaging. • Increasing available outlets for bulk sale. • Providing power outage solutions for refrigeration at the household level. • Making efforts to influence and sustain behavior changes at high- and mid- income household levels.
	Organic waste diversion: Source separation of organics	**Cost of Source Separation of Organics Programs** • Organic separation is more costly due to less-efficient collection, space constraints, enhanced sanitation protocols, additional labor, and equipment purchase and maintenance. • It could be particularly burdensome in lower-income communities.	• Incentivizing source separation of organics through subsidies or other funding mechanisms.

[1] Ebun Ayandele, Kenzie Huffman, Matt Jungclaus, Eugene Tseng, Riley Duren, Daniel Cusworth, and Bryan Fisher, "Key Strategies for Mitigating Methane Emissions from Municipal Solid Waste," RMI, 2022, https://rmi.org/insight/mitigating-methane-emissions-from-municipal-solid-waste/.

Category	Strategy	Key Considerations	Potential Interventions
Pre-land disposal site strategies	Organic waste diversion: Source separation of organics	**Behavioral Patterns** • Organic separation requires households and businesses to become more intentional in how they discard waste. • Community concerns about uncleanliness, odor, and rodent/pest infestations can hinder the adoption of organic separation programs.	• Offering continued educational campaigns and awareness programs about different waste types and their effective disposal. • Encouraging or supporting composting activities at household or community level.
		Enabling Regulations • Organic separation requires incentivization or mandatory participation of households and businesses.	• Applying the regulations either to everyone or only to entities (commercial places, schools, hospitals, etc.) that generate a high volume of waste.
	Organic waste diversion: Organic recovery from mixed waste	**Upfront Costs** • The capital cost of developing or purchasing automated technology may discourage adoption. • Covering this expense can be challenging, especially for smaller landfills, especially in developing countries. • Where the economic viability of such technologies has yet to be proven, high interest rates may exacerbate the barriers to securing financing.	• Incentivizing landfill owners to adopt materials recovery technologies through subsidies or lower interest loans.
		Technical and Economic Viability and Commercial Availability • Organic waste diversion requires developing and/or upgrading materials recovery facilities to also recover food waste with commercial viability and availability of technologies.	• Facilitating the broader adoption of technology by conducting assessments to verify their technical effectiveness—particularly for nascent technologies—and economic viability.
Land disposal site strategies	Dump site rehabilitation	**High Upfront Cost** • There can be a lack of funds to build comprehensive waste management systems.	• Improving access to affordable capital and supporting the understanding of available funding mechanisms to help fund expensive capital projects, such as rehabilitation of open dump sites.
		Lack of Regulatory Frameworks and Oversight • Many countries do not have comprehensive regulatory frameworks for solid waste management.	

Category	Strategy	Key Considerations	Potential Interventions
Land disposal site strategies	Dump site rehabilitation	**Limited or Unavailable Data** • Better waste and emissions data could facilitate upgrading dump sites to sanitary landfills with methane capture systems, particularly when resources are constrained.	• Developing countries: Incorporating data collection mechanisms to address data gaps when building regulatory frameworks. • Regulators: Requiring waste disposal facilities to periodically perform methane surveys and report their greenhouse gas emissions.
		Need to Build Local Capacity • Due to limited technical and financial resources in emerging economies, the upgrading of dump sites and development of methane mitigation projects often rely on experts in developed countries where these solutions are already implemented.	• Involving local communities in solution development and decision-making, investing in technical development programs, and hiring local companies, among other activities, to help secure buy-in, create economic opportunities, and ensure a project's long-term success.
		Sensitivity to Local Cultural Context • Need to consider social, cultural, and economic factors, such as the impacts on waste pickers, who depend on informal waste collection for their livelihoods.	• Relying on local expertise (technical and nontechnical) to help embed methane management solutions into the communities where they are being developed, enhancing the long-term success of these solutions.
	Landfill design and operation	**Holistic System Design** • Landfills are dynamic and complex systems, and each site is unique.	• Taking a whole-systems approach to design and operations to ensure that interactions within the system do not conflict with each other to result in a negative outcome.
		Lack of Complete, Precise, and Timely Emissions Data • To mitigate landfill methane, operators must be able to rapidly identify, quantify, and pinpoint high emissions (from leaking equipment and process errors); take action to mitigate those emissions; and assess the effectiveness of the mitigation measures.	• Enabling flexible regulatory frameworks for monitoring that establish standards on sample frequency, detection limits, and spatial coverage for high-emissions events to incentivize advanced technologies that fill existing gaps.

Category	Strategy	Key Considerations	Potential Interventions
Land disposal site strategies	Landfill design and operation	**Permitting Delays** • Proposals for new landfills and other waste management facilities and upgrades to existing facilities often trigger complex permitting processes that can add months, and in some cases years, to projects, increasing costs and disincentivizing developers from making important design or operational updates that would significantly address methane emissions.	• Enacting permitting reforms focused on facilitating approvals of pollution reduction projects, alongside enhanced community engagement efforts, to potentially speed the permitting process for beneficial projects while addressing community concerns.
		Regulatory Capacity and Enhanced Coordination • Regulatory requirements are necessary to maximize methane reduction opportunities that fully deploy the optimal mitigation measures at the landfill, and successful regulation requires adequate regulatory capacity.	