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Review

Enhancing municipal solid waste stabilization through sustainable aerobic landfill technologies

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ABSTRACT

Aerobic bioreactor landfills (ABRLs) offer promise for rapid waste stabilization, superior leachate quality, and substantial methane mitigation; however, a holistic synthesis of their diverse aeration strategies and emerging innovations remains lacking. This review critically evaluates ABRL operational principles, configurations, and performance metrics and quantifies outcomes reported in laboratory, pilot and field lysimeter experiments. Across the studies compiled, leachate chemical oxygen demand (COD) reductions ranged from roughly 50 % to >99 %, with the majority of experiments reporting ≥85 % COD removal under aerobic/recirculation regimes. Waste settlement measured in these trials varied from ~25 % to 62.5 %. Experiment durations for lab/pilot lysimeters most commonly fell between ~80 and 600 days, while larger-scale/longer-term projects reported multi-year observational windows and continued stabilization trends. Besides, fundamental mechanisms of aerobic degradation are outlined, with a comparison of horizontal versus vertical aeration and leachate-based oxygen delivery systems. The influence of aeration on key performance indicators ammonia-nitrogen removal, chemical oxygen demand reduction, waste settlement, and off-gas composition is examined in detail. Advanced leachate recirculation techniques, including micro-aeration, pure-oxygen oxygenation, and H_2O_2 pretreatment, are explored to highlight their roles in enhancing microbial activity and accelerating stabilization. Technical challenges like oxygen-distribution heterogeneity, moisture management, and high energy demands are subsequently identified, and monitoring and design strategies are proposed to overcome these barriers.

By synthesizing global case studies and quantitative performance data, this review addresses a critical gap in the literature and provides actionable insights to guide researchers and practitioners toward more sustainable landfill-management practices that align with climate-mitigation goals.

Abbreviations

MSW - Municipal Solid Waste	NH_4^+-N - Ammonium Nitrogen
kg - Kilogram	T-N - Total Nitrogen
CO_2 - Carbon Dioxide	L/min - Liters per Minute
CH_4 - Methane	COD_{peak} - Peak Chemical Oxygen Demand
EU - European Union	k_{COD} - First-order Rate Coefficient for COD Removal
LFG - Landfill Gas	L min^{-1} kg^{-1} DOM - Liters per Minute per Kilogram of Dry Organic Matter
COD - Chemical Oxygen Demand	DOM-Dry Organic Matter
NH_3-N - Ammonia Nitrogen	d^{-1} - Per Day
O_2 - Oxygen	°C - Degrees Celsius
WtE - Waste-to-Energy	pH - potential of Hydrogen
ABRL - Aerobic Bioreactor Landfill	N_2 - Nitrogen
EPA - Environmental Protection Agency	VOCs - Volatile Organic Compounds
TCA - Tricarboxylic Acid	HTs - Horizontal Trenches
ATP - Adenosine Triphosphate	VWs - Vertical Wells
GHG - Greenhouse Gas	TKN - Total Kjeldahl Nitrogen
NH_3 - Ammonia	TP - Total Phosphorus
BOD_5 - Biological Oxygen Demand (measured over 5 days)	MWOAM - Multi-Well Optimization Method
	WS - Well Spacing
	OSR - Oxygen Storage Ratio
	RA_4 - Respiration Activity over 4 days

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TOC – Total Organic Carbon	GP_{21} - Gas Generation Potential over 21 days
DSBS - Dual Step Bio stabilization System	C/N - Carbon to Nitrogen Ratio
NO_3^- - Nitrate	
NO_2^- - Nitrite	
CO - Carbon Monoxide	H_2S - Hydrogen Sulfide
GWP – Global Warming Potential	N_2O - Nitrous Oxide
	LCS – Leachate Collection System

1. Introduction

The high consumption rates of energy and goods, coupled with increasing population growth and high standards of living, lead to significant MSW generation, posing serious environmental threats if not effectively disposed of or recycled. Currently, an estimated 2 billion tonnes of MSW are generated globally, with approximately 33 % remaining uncollected by municipalities (Eghbali et al., 2022; Kaza et al., 2018). Of the total MSW collected by municipalities, about 70 % ends up in landfills and dumpsites, 19 % is recycled, and 11 % is used for energy recovery (Kaza et al., 2018). According to the World Bank, MSW generation is projected to rise to 3.4 billion tonnes by 2050 (Kaza et al., 2018). Landfills already produce about 11 % of the world's methane emissions, a figure set to increase by around 7 % by mid-century due to population expansion and, since methane is 80 times more potent a greenhouse gas than CO_2 over a 20-year period, reducing methane emissions now can have an immediate and significant impact on mitigating climate change (Kaza et al., 2018; Dai and Wang, 2024). Despite EU Commission legislation aimed at minimizing landfilling (Abdel-Shafy and Mansour, 2018; Osazee, 2021), landfills remain an essential component of solid waste management systems. Sustainable landfilling emphasizes early waste stabilization and greenhouse-gas reduction to protect future generations from environmental risks and costly remediation (Ban et al., 2015; Ozbay et al., 2021; Song et al., 2023).

Various bioreactor landfill technologies have been developed to accelerate MSW breakdown and improve leachate treatment (Cossu et al., 2016; Hirata et al., 2012; Slezak et al., 2015; Xu et al., 2014). In anaerobic bioreactors, moisture addition and leachate recirculation enhance methane generation, achieve better leachate quality, and shorten stabilization and monitoring times compared to conventional anaerobic landfills (Valencia et al., 2011; Christensen et al., 2011). However, anaerobic conditions can lead to excessive ammonia accumulation in leachate often approaching 2000 mg/L which promotes algal blooms, depletes dissolved oxygen in receiving waters, and exerts toxic effects on aquatic organisms (Dos Santos et al., 2020). Furthermore, anaerobic landfills impede the microbial growth necessary for organic-waste biodegradation (Viegas et al., 2021), resulting in stabilization periods spanning decades (Lee et al., 2022). These long timeframes consume vast land areas and constrain urban development (Huang et al., 2022), although post-closure repurposing for commercial or residential use can mitigate pollution risks and support urban expansion (Zhang et al., 2023).

The aerobic process is perceived as a better alternative to anaerobic landfills under the sustainable-landfilling concept because it provides faster improvements in leachate quality through removal of ammonia-nitrogen and chemical oxygen demand (COD) along with lower methane emissions and accelerated waste stabilization (Nikolaou et al., 2009; Grossule et al., 2018; Shao et al., 2008; Tong et al., 2015). Interest in aerobic landfills has recently increased, prompting investigations at both laboratory and field scales for their ability to improve waste stabilization, generate less harmful leachate, and prevent methane emissions, thus offering a promising solution to the shortcomings of conventional anaerobic landfills (Hashisho and El-Fadel, 2014).

Numerous studies have utilized aerobic bioreactors landfills (ABRLs) to assess waste decomposition and leachate quality (Ko et al., 2016; Slezak et al., 2015; Xu et al., 2015; Falamaki et al., 2019; Qiu et al., 2020; Chu et al., 2021; Ma et al., 2021). These systems stimulate microbial activity by simultaneously supplying moisture and air, leading to faster removal of ammonia-nitrogen and COD, and lower methane emissions (Shao et al., 2008; Tong et al., 2015). However, ABRLs often involve forced ventilation systems, complex operation, and high energy usage resulting in significant capital and operating expenses (Slezak et al., 2015).

Aeration is central to ABRL performance as it improves leachate quality and expedites stabilization (Xu et al., 2025) and is also applied to remediate older landfills by reducing emissions from prolonged anaerobic degradation (Raga and Cossu, 2014; Ritzkowski et al., 2006; Zieleniewska-Jastrzebska et al., 2007). Forced aeration has emerged as a preferred method for stabilizing waste, lowering nitrogen levels, and managing emissions (Hrad et al., 2013; Ritzkowski and Stegmann, 2005), and serves as a key pretreatment step in landfill mining (Raga and Cossu, 2014; Ritzkowski and Stegmann, 2012). Although flushing can be effective (Bolyard and Reinhart, 2016), it demands substantial water and costly off-site leachate treatment (Ritzkowski et al., 2006). Recently, Song et al. developed an air amplifier using the Coandă effect to cut power consumption by 90 % while increasing airflow 3.5-fold, achieving 90.3 % methane reduction efficiency demonstrating a cost-effective aeration solution (Song et al., 2023).

This review article aims to critically examine and synthesize current knowledge and advancements in aerobic landfill technologies as a sustainable approach to MSW management. By providing a comprehensive overview of ABRL principles, methods, and impacts, the article highlights their benefits and challenges. While previous reviews have often focused on traditional anaerobic techniques or specific aerobic aspects, this work fills critical knowledge gaps by analyzing diverse aeration methods (e.g., horizontal and vertical aeration, leachate collection systems) and their direct effects on performance metrics such as ammonia-nitrogen levels, leachate COD, and waste settlement. It also explores innovative leachate recirculation trends such as micro-aeration, oxygenation, and H_2O_2 pretreatment that are rarely covered comprehensively. Finally, the review offers recommendations and future perspectives to guide further research and implementation of sustainable waste management practices.

2. Landfill technologies and evolving trends

MSW generation worldwide is increasing dramatically under population growth, urbanization, and consumerism, with an estimate of around 2.01 billion tons per year, projected to grow by 2050 to 3.40 billion tons. There were an estimated 468 million metric tons of waste generated by East Asia and the Pacific in 2016, with projections to reach 714 million metric tons in 2050 (World Bank, 2018a,b). This growth highlights the need for comprehensive waste management strategies to address the projected MSW increase from 2016 to 2050 (Fig. 1). Landfilling remains a prevalent choice due to cost-effectiveness, available infrastructure, and public acceptance, with millions of tons of waste directed to the world's largest landfills annually (Fig. 1b). For instance, the Sudokwon landfill in Incheon, South Korea, receives about 6.9 million tons of waste per year, while the Bordo Poniente landfill in Mexico City, Mexico, handles 4.4 million tons annually. The Deonar landfill in Mumbai, one of India's oldest, faces critical space and pollution challenges. Meanwhile, Apex Regional landfill, USA ranks thirdin terms of annual waste disposal, handling over 3.8 million tons annually. These figures underscore the pressing need for sustainable practices as urbanization increases, emphasizing global efforts to mitigate landfill-related environmental impacts.

Municipal waste is still largely managed by disposal in engineered landfills, which remain the cheapest and most familiar option worldwide. For context, global MSW is projected to increase by about 70 % by 2050 (Kaza et al., 2018), and landfilling (especially in low and

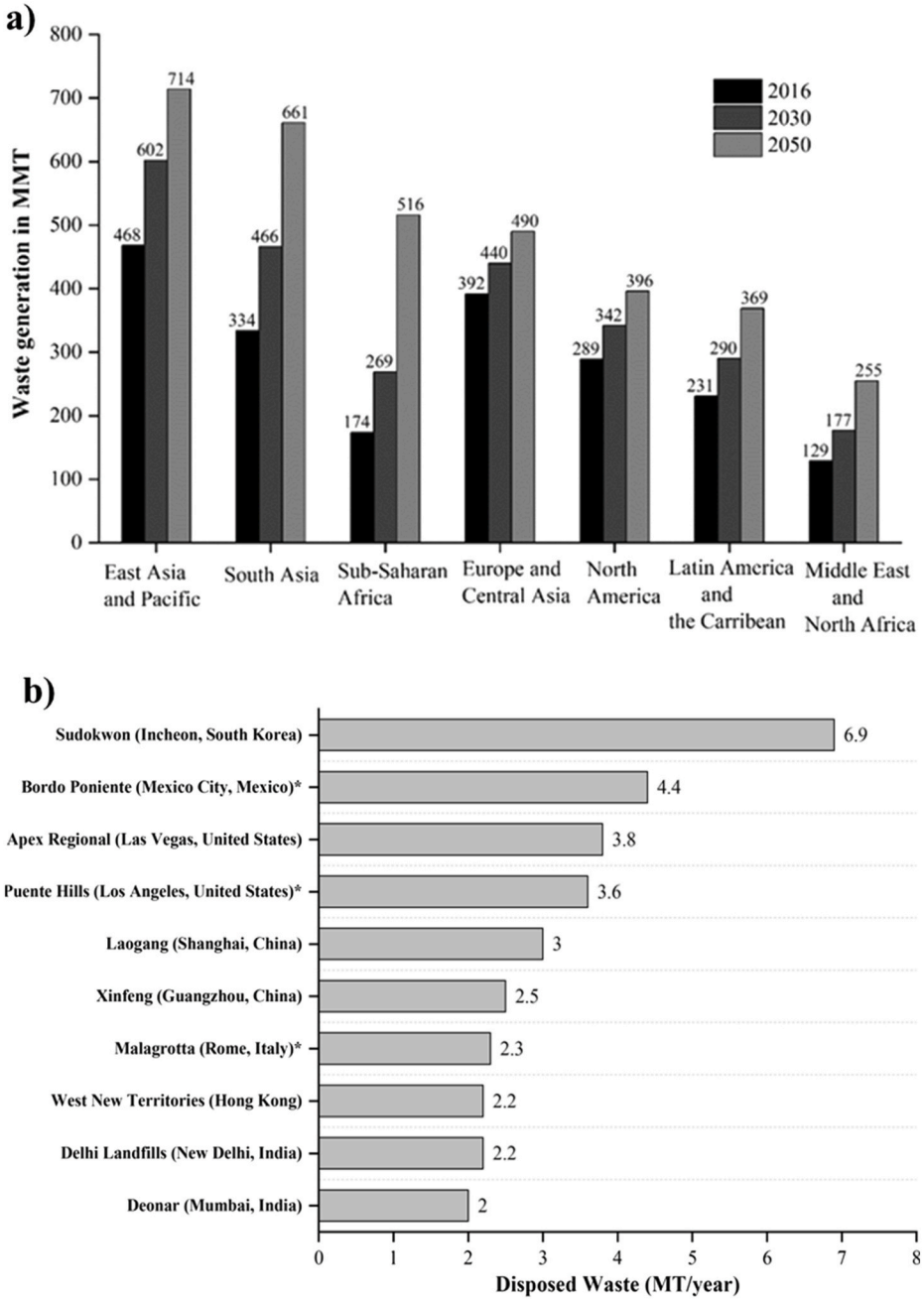


Fig. 1. a) Projected global generation of municipal solid waste from 2016 to 2050 (in million metric tons) and b) annual volume of waste disposed at the largest landfills worldwide (in million tons) (Data source: World Bank, 2018a,b; Owlcation. (April 5, 2024)). *Permanently closed.

middle-income countries) handles the bulk of this growth. Fig. 2 shows the evolution of landfilling technologies showing a progression from conventional anaerobic landfills, which emit methane and discharge untreated leachate, to semi-aerobic systems with passive venting and partial leachate improvement, and finally to aerobic bioreactor landfills that use active air injection and leachate recirculation to accelerate waste stabilization and reduce environmental impacts.

Conventional landfills are typically operated as anaerobic "dry tombs" where wastes are buried under caps and liners, with little liquid or air intentionally added (US EPA, 2025). This design aims simply to isolate waste, so decomposition is slow and dominated by anaerobic microbes. As a result, stabilization can take decades or longer and large volumes of methane are emitted before closure.

Semi-aerobic (Fukuoka) landfills occupy a middle ground. These systems use perforated leachate drains and passive venting to admit air by natural convection, without active blowers or forced aeration (Fig. 2). The goal is to approximate aerobic conditions at low cost. Japan's Fukuoka method is the classic example where studies report that this low-tech design cuts greenhouse gas emissions roughly in half compared to conventional sanitary landfills, while requiring only simple drains and caps (World Bank, 2020). The Fukuoka approach has been adopted in many countries (an estimated 17 nations have applied it) and is especially popular where technical resources are limited (Kaza et al., 2018). Experimental and full-scale comparisons show semi-aerobic cells speed up organic decay (improving carbon and nitrogen removal) and suppress methane formation relative to fully anaerobic landfills (Grossule et al., 2018). These benefits make semi-aerobic systems attractive for developing countries; in fact, dozens of semi-aerobic projects now operate in both industrialized (e.g. Japan, Italy) and developing nations (e.g. China, Iran, Malaysia, Vietnam) (Grossule et al.,

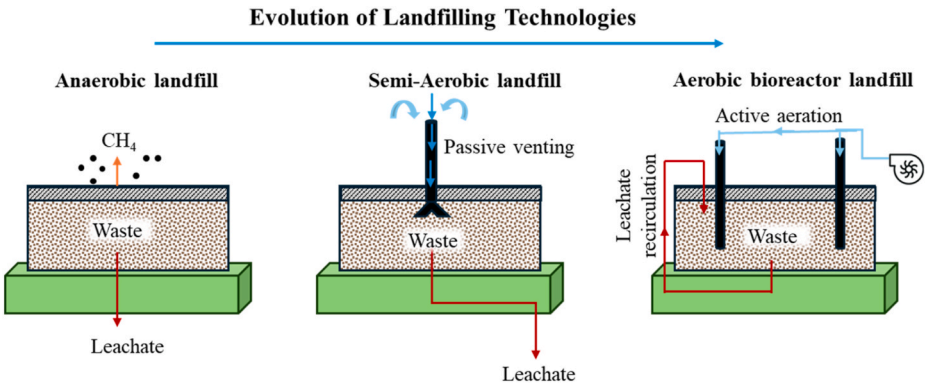


Fig. 2. The evolution of landfilling technologies (anaerobic, semi-aerobic, and aerobic bioreactors).

2020). However, maintaining the right moisture balance can be challenging in semi-aerobic landfill performance in tropical climates as it is affected by seasonal changes where dry periods can reduce biodegradation due to low moisture, while heavy rains in the wet season may increase emissions and leachate generation (Grossule et al., 2020).

At the top end of the spectrum are aerobic bioreactor landfills, which inject air into the waste mass by pumps or blowers. In an aerobic landfill, leachate is recirculated to maintain moisture, but importantly air is injected into the waste mass using vertical or horizontal wells to promote aerobic activity and accelerate waste stabilization (US EPA, 2025). Under these oxygenated conditions, biodegradation is rapid where organics are oxidized mostly to CO_2 and water rather than methane. Aerobic landfills thus cut off the major source of landfill methane (a GHG ≈25 × stronger than CO_2) and can consume high-strength waste contaminants (e.g. ammoniacal-N) more completely. The trade-offs are higher energy use for blower operation and potential nitrous-oxide release, but the overall result is much faster stabilization. Indeed, EPA guidance notes that bioreactor operation can reduce stabilization times from decades to just years. Site demonstrations in the US have shown aerobic cells reach near-stabilization in only a few years, with very low residual gas emissions (US EPA, 2025). Because wastes break down so much faster, aerobic bioreactors also recover landfill airspace more quickly and reduce the duration of post-closure care. Many landfill operators simply refer to any system with active aeration as an "aerobic" bioreactor, even if some methanogenesis still occurs later in some anaerobic pockets. Regulatory support for these engineered methods is growing. For instance, the US EPA's 2004 bioreactor rule explicitly allows liquid and air addition under permit, and by 2014 there were ~40 bioreactor landfill projects (anaerobic, aerobic or hybrid) underway in North America (EPA, 2017). International experience mirrors this trend, for example, Japan pioneered semi-aerobic landfill for enhanced degradation, while in the US operators use aeration to speed settlement and maximize capacity, and in Europe the emphasis is on in-situ aeration of legacy sites to achieve a controlled reduction of emissions and shorten aftercare (Hamburg University of Technology, 2023). In summary, waste management is gradually shifting from passive disposal toward active, bioreactor-based strategies. This evolution provides the context for the present review. In the sections that follow we focus on aerobic bioreactor landfills as an emerging, sustainable approach to landfill management, with the potential to greatly reduce methane output and accelerate waste stabilization.

3. Aerobic bioreactor landfills (ABRLs)

3.1. Overview of aerobic bioreactor landfill concept

In recent years, aerobic bioreactor landfill technology has gained increasing attention because of the noted benefits (Rich et al., 2008, Ritzkowski et al., 2007). Aerobic conditions inhibit acidogenic fermentation, preventing pH from dropping below the optimal range for key degradative microbes and thus maintaining high rates of organic breakdown. This pH stability decreases the solubility of heavy metals, promoting their adsorption onto biomass and solid phases rather than mobilization into leachate. Reduced acid production also limits the formation of refractory humic and fulvic acids, yielding leachate with lower COD and simpler organic composition. By curtailing both acid leachate generation and metal mobilization, aerobic conditions significantly reduce the volume and toxicity of leachate that would otherwise require off-site treatment (Rittman and McCarty, 2001). This approach has been implemented in several countries, including Japan, Germany, and the United States (Falamaki et al., 2019). Aerobic bioreactor landfills are designed to address the dehydration issues common in simple aerobic landfills, where injected air can dry out waste and inhibit microbial activity. By actively recirculating leachate or other liquids, aerobic bioreactors maintain optimal moisture levels (35–65 % by weight), ensuring sustained microbial degradation. Studies have shown the effectiveness of this approach. Karimi and Bareither (2021) reported higher decay rates and shorter lag times in reactors with enhanced moisture addition, while Nwaokorie et al. (2018) observed a doubling of the effective decay constant (from 0.04 yr^{-1} to 0.08 yr^{-1}) through leachate recirculation. Thus, by supplying both moisture and oxygen, aerobic bioreactor landfills significantly accelerate waste stabilization compared to conventional aerobic systems. These systems introduce oxygen into the landfill environment to promote aerobic conditions, often employing horizontal and vertical wells similar to those used for gas extraction and leachate injection. ABRLs accelerate waste decomposition by creating oxygen-rich environments conducive to aerobic microorganisms. These microorganisms obtain energy through the oxidation of organic compounds, primarily producing carbon dioxide (CO_2) and water. Biodegradation happens much more quickly and efficiently when oxygen is present because oxygen serves as the final electron acceptor in the process. In contrast, when oxygen is absent under anaerobic conditions other substances like nitrate, sulfate, or iron take on that role. However, these alternatives are far less effective, so the breakdown of pollutants tends to be much slower, and in some cases, almost insignificant compared to what we see in aerobic environments (Pandolfo et al., 2023) Key elements of ABRLs include a robust bottom liner that prevents leachate from contaminating groundwater, a network of air injection wells that distribute air throughout the waste mass to maintain aerobic conditions, and a leachate collection system that recirculates leachate back into the waste mass (Fig. 3).

This air injection inhibits the growth of anaerobic microorganisms, resulting in a decrease in methanogenesis and methane (CH_4) formation. Air injection methods in ABRLs include active aeration with off-gas extraction, active aeration without off-gas extraction, passive aeration, intermittent high-pressure aeration, and intermittent low-pressure aeration (Ritzkowski and Stegmann, 2012). Additionally, landfills are equipped with gas collection systems to capture and manage emissions,

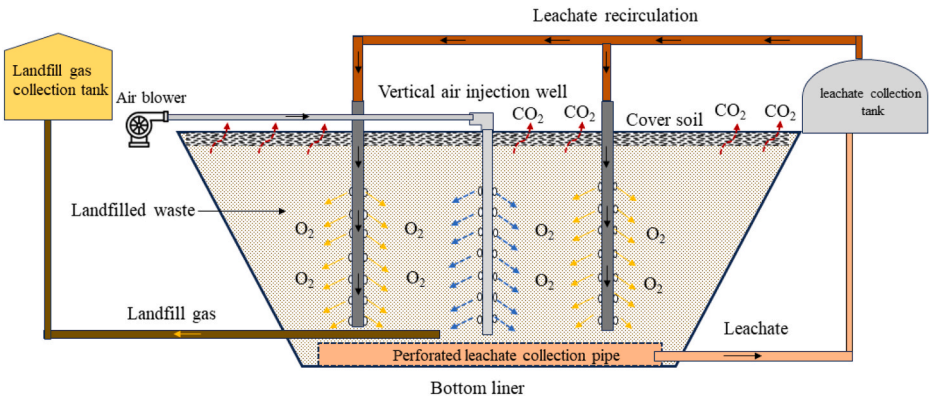


Fig. 3. A schematic representation of an aerobic bioreactor landfill includes landfilled waste actively aerated through a network of pipes to promote microbial decomposition, supplemented by a leachate collection and recirculation system, and gas collection mechanisms. Redrawn and modified based on data from Nanda and Berruti (2021)

primarily CO_2, generated during decomposition. Daily cover materials and a final cap serve to minimize odors, pests, and wind-blown debris while preventing excess water infiltration. The rate of aerobic biodegradation is influenced by several factors, including aeration rate, waste compaction density (Qiu et al., 2020), mesophilic temperatures, moisture content, and pH levels (Omar and Rohani, 2015) (Table 1).

In situ aeration is primarily intended to oxidize and transform the emission behavior of landfills, reducing their emission potential more effectively (Mudhoo et al., 2013). Aerobic degradation mechanisms occurring in landfills allow for a much rapid decline of organics, such as hydrocarbons, in comparison to anaerobic processes. Consequently, the enhanced aerobic oxidation of organic matter leads to the transformation of carbon compounds into gaseous forms, primarily CO_2, thereby increasing carbon discharge in the gas phase and reducing the concentration of dissolved organic carbon (DOC) and COD in the leachate. Notably, nitrogen elimination stands out as the most significant advantage achievable through aeration technology. A comparative summary of the different aspects of ABRLs and traditional anaerobic landfills is illustrated in Table 2.

Table 1
Key Operational parameters for aerobic bioreactor landfills.

Operational parameter	Impact on Landfill Performance	Optimal range	Reference
Moisture content	- Excess moisture can lead to reduced aeration efficiency and higher leachate production. - Low moisture can hinder microbial activity, slowing waste degradation.	- Ideal moisture content 50 %–60 % - Optimum microbial growth	Peng et al. (2024); Zhang et al. 2023
Waste compaction density	- Higher compaction improves landfill capacity - May reduce pore spaces for air and water movement, hindering aerobic microbial activity	- Compaction: 550 kg/m^3 - Promotes better biodegradation	Qiu et al. (2020)
Aeration rate	- Higher aeration rates increase energy costs and low moisture - Aeration rate >0.3 L min^{-1} kg^{-1} Dry Organic Matter (DOM) reduces the kCOD	- Aeration rate 0.1–0.3 L min^{-1} kg^{-1} DOM - Best enhancement on the k_{COD}	Ma et al. (2021) Lwin et al. (2024)
Temperature	- Thermophilic temperature (50–60 °C) inhibits nitrification	– 22–45 °C - Promotes biodegradation and accelerates stabilization	Qiu et al. (2020); Raga and Cossu (2013)
pH	- pH should not be extremely acidic or basic	Optimum pH: 6.5–8.5	Nanda and Berruti, 2021; Omar and Rohani, 2015

Table 2
Comparative summary of the different aspects of aerobic bioreactor landfills and traditional anaerobic landfills.

Aspect	Anaerobic landfills	Aerobic Bioreactor landfills	Reference
Stabilization time	Long stabilization time	Short stabilization time	Slezak et al., (2015), Rich et al., (2008)
Landfill gas	- Produces methane (CH_4) and carbon dioxide (CO_2) - High global warming potential (GWP) of CH_4 (25 times that of CO_2)	- Produces mainly CO_2 - Reduces GWP	Song et al. (2023); Wang et al. (2017)
Leachate quality	- High levels of VFA, H_2S and ammonia	- Reduces VFA and ammonia content - Lower COD, BOD_5 - Reduces odor	Omar et al. 2015
Energy requirements	- Minimal energy required	- High energy demand for aeration	Nag et al. (2018)
GHG emissions	- High potential for GHG emissions if gas is not effectively captured	- Lower GHG emissions	Omar et al. 2015
Environmental impacts	- Slower organic waste breakdown increases long-term environmental risks	- Faster stabilization reduces risks of leachate and gas migration	Fadel et al. (2013)
Economic implications	- Gas Collection Revenue: Methane can generate revenue if captured and sold as energy - Leachate treatment costs: High due to high concentrations of contaminants - Long-term liability: Extended monitoring and remediation costs	- Upfront investment: High for aeration infrastructure. - Reduced Monitoring Costs: Faster stabilization reduces post-closure care - Leachate treatment costs: Lower due to improved quality	Berge et al. (2009)

Unlike anaerobic methods, ABRLs supress production of methane (Hashisho and El-Fadel, 2014) or other odorous gases and can break down chemical compounds resistant to anaerobic degradation, enhancing treatment for organic wastes and ammonia. The introduction of air helps reduce moisture, and leachate production. In general, aerobic stabilization of waste helps to reduce its volume, weight, and potential for producing biogas, and the extent of this reduction depends on how long the process lasts (Ali et al., 2018). According to Berge et al. (2009), ABRLs are about 13 % less expensive than traditional landfills due to savings in landfill space, allowing for more waste placement before needing additional cells. Leachate from these landfills has lower COD, BOD, and TOC levels, with very little ammonia. Aerobic landfill operations characterised by oxygen concentrations of at least ~5 % in the waste mass, moisture contents maintained at 40–70 %, and active air/oxygen injection promote aerobic microbial degradation of organics to CO_2 and H_2O and thereby suppress methane generation from anaerobic pathways (Read et al., 2001a,b; Hashisho and El-Fadel, 2014, Feng et al., 2021). Although aerobic conditions in landfills prevent methane production and thus eliminate the possibility of recovering energy from landfill gas, they provide clear environmental benefits over anaerobic landfills, chiefly by substantially reducing greenhouse gas emissions. Under the assumption of global adoption and based on methane's high global warming potential, Omar and Rohani (2015) estimated that a full shift to aerobic landfill treatment could reduce atmospheric greenhouse gas emissions by an amount equivalent to at least 761 million metric tons of CO_2 annually (methane mitigation as CO_2 equivalent). This estimate, however, depends on factors such as waste composition, landfill age, operational efficiency, and does not account for CO_2 emissions from the energy required for aeration.

3.2. Principles of aerobic degradation

Aerobic degradation in landfills is a biologically driven process that occurs in the presence of oxygen, promoting faster and more environmentally friendly stabilization of organic waste. The primary biochemical pathway is summarized in Fig. 4. Air, either naturally diffused or artificially supplied into the waste using either vertical or horizontal wells to promote aerobic conditions, activating aerobic microbes which accelerates the decomposition of waste (EPA - Environmental Protection Agency, 2017). The process begins with hydrolysis, where large organic molecules like carbohydrates, proteins, and fats are broken down into simpler, soluble forms such as sugars and amino acids by microbial enzymes. These simpler compounds are then metabolized in the aerobic oxidation stage, during which oxygen is used to convert them into carbon dioxide, water, and energy. This step generates heat, raising landfill temperatures and further accelerating decomposition. This exothermic reaction can elevate in-situ temperatures to as high as 66 °C (Moreno, 2017), especially in actively aerated zones. Although high temperatures and the presence of oxygen could theoretically raise the risk of spontaneous ignition, this is typically mitigated by the substantial reduction in methane production, as aerobic processes divert carbon flux from methanogenesis toward CO_2 production. Methane, being highly flammable, is largely absent under well-managed aerobic conditions.

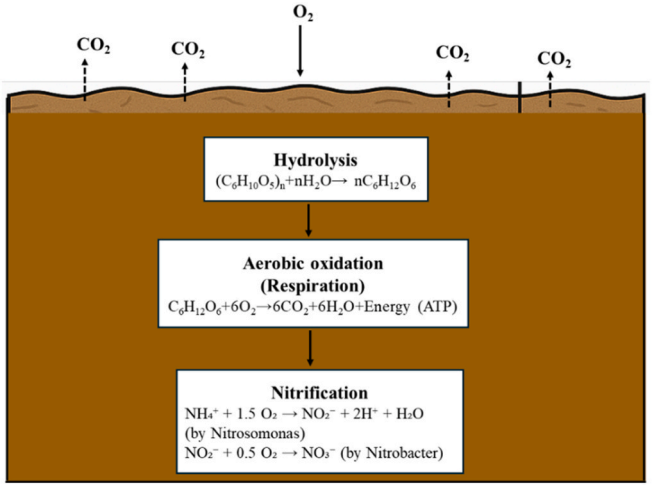


Fig. 4. Schematic representation of aerobic degradation of organic fraction of MSW.

The increased temperature enhances evaporation within the waste matrix, subsequently reducing the volume of leachate that must be collected and treated. However, while this thermal effect offers leachate management benefits, it also poses a risk of desiccation. When moisture content drops below the optimal range (typically 35–65 % by weight), microbial activity slows significantly, leading to incomplete degradation (Berge et al., 2005). This highlights the importance of maintaining near field-capacity moisture through controlled leachate recirculation or supplemental liquid addition in aerobic bioreactor landfills. Under aerobic conditions, the redox potential shifts from strongly negative to positive, influencing both metal behaviour and enhancing the breakdown of organic compounds. This shift favours aerobic respiration, where oxygen serves as the primary electron acceptor, resulting in the effective degradation of organic matter (Rolle et al., 2005).

Another important step is nitrification, where ammonia released from nitrogen-rich waste is oxidized first to nitrite and then to nitrate by specialized bacteria. Aerobic processes enhance nitrogen transformations and removal methods such as nitrification and ammonia air stripping or volatilization. Such conditions elevate pH through microbial degradation of organic acids producing endogenous alkalinity, aeration-driven CO_2 stripping reducing carbonic acid buffering, and heat generation from aerobic reactions, which raises temperatures to 30–40 °C (Trinh et al., 2025). These conditions collectively increase pH (to around 8–9) and promote ammonia (NH_3) volatilization and reduces its solubility (Smaoui et al., 2020). The increased gas flow from air injection further facilitates the removal of ammonia nitrogen due to enhanced mass transfer (air-stripping) and improved oxygen delivery for nitrification (Berge et al., 2005). This transformation reduces the toxicity of landfill leachate and reduces the generation of odorous and toxic compounds such as methane and free ammonia. This not only improves environmental outcomes but also offers social advantages by minimizing odor nuisance and health risks associated with landfill gas and leachate emissions. Throughout this process, microbes consume oxygen and produce CO_2 and water as primary by-products.

The diagram (Fig. 5) illustrates how ammonium (NH_4^+) produced by the mineralization of organic nitrogen in waste follows distinct pathways in aerobic versus anaerobic landfill environments. In the aerobic landfill, NH_4^+ is first transformed via two-step nitrification (by *Nitrosomonas* and *Nitrobacter*) into nitrate (NO_3^-), and any localized oxygen-deficient zones may carry out partial denitrification all the way to N_2 gas. Concurrently, at pH $\geq$ 9, NH_4^+ can strip into the gas phase as NH_3. In anaerobic (methanogenic) landfill zones, anammox is only feasible under strict conditions. Anammox bacteria require near-anoxic conditions (DO $\ll$ 0.5 mg/L) (Cho et al., 2019) and low biodegradable carbon (e.g. BOD_5/COD ~0.1) so that heterotrophs do not outcompete them (Deng et al., 2022). Typical NH_4^+–N is high (>2000 mg/L) but free-NH_3 should be < 35–40 mg/L to avoid inhibition (Deng et al., 2022). The optimal pH for anammox is 6.7–8.3 (Miao et al., 2019), which matches the typically alkaline leachate (pH ~7.5–8). Temperatures in the 30–40 °C range give maximal anammox rates (Cho et al., 2019), whereas below ~20 °C performance drops sharply. Under these conditions, anammox bacteria converts NH_4^+ and NO_2^- to molecular nitrogen (N_2) (Botchkova et al., 2023; Deng et al., 2022).

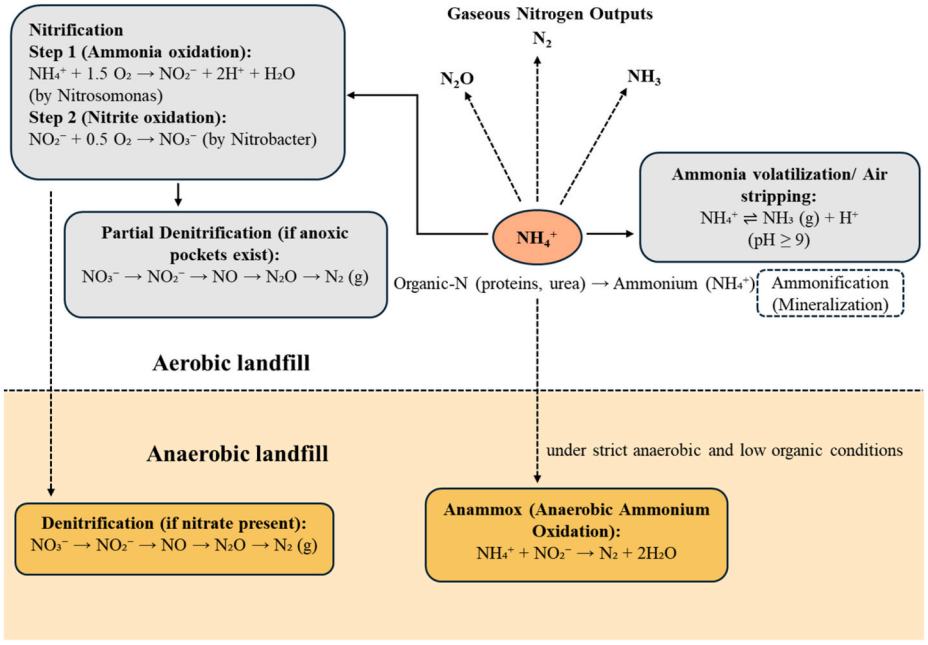


Fig. 5. Nitrogen dynamics during solid waste degradation in aerobic and anaerobic landfills.

4. Different methods of landfill active aeration

Active aeration systems use forced air to create aerobic conditions and accelerate waste stabilization. Air is typically supplied via engineered wells or piping and removed by vents or gas collectors, so that oxygen reaches buried waste. Positive aeration means blowing air into the waste (e.g. with blowers into injection wells), while negative aeration (vacuum) means drawing gas out and thereby pulling fresh air in. For example, Dillon et al. (2023) describe active aeration concepts where air is forcibly introduced into landfills, consuming energy via injection (positive aeration) or suction (negative aeration). In practice, any injection or extraction well can be used in either mode.

4.1. Horizontal aeration

Horizontal aeration is employed in landfills to promote aerobic waste decomposition by infusing air through excavated channels or trenches. In this method, trenches are dug across the landfill layers and equipped with perforated pipes or channels to serve as pathways for air distribution. The air is either blown or pumped through these channels into the landfill, permeating the waste layers and supplying oxygen to aerobic microbes. Brandstätter et al. (2020) conducted a field-scale study on an in-situ aeration project, demonstrating that horizontal landfill aeration achieved extensive air distribution across a relatively shallow landfill. Bartholamuez and Hettiaratchi (2016) assessed various aeration configurations in aerobic landfill lysimeter experiments and found that horizontal aeration systems led to the formation of localized anaerobic zones. Aeration was most effective in the upper layers of the lysimeter, while the lower layers experienced significantly reduced aeration. This suggests that shallower piping systems are required for optimal aeration if horizontal systems are to be used.

Despite its advantages, the efficacy of horizontal aeration depends on meticulous design and execution. The layout, depth, and spacing of trenches or channels demand thoughtful planning to guarantee uniform air distribution and efficacious aeration. Monitoring mechanisms should be deployed to gauge oxygen levels, temperature, and gas emissions within the landfill, enabling operators to fine-tune the aeration process as required. Routine maintenance and checks are imperative to promptly identify and rectify issues like pipe blockages, settling, or gas seepage that could affect the aeration system's performance or the landfill's structural integrity.

While this method allows localized gas migration, some anaerobic pockets may form, leading to only partial effectiveness in waste degradation. The cost is moderate, as installation is easier during landfill operations. However, pipes may clog or collapse due to waste settlement. This system provides moderate performance and is best suited for new or shallow landfills where aeration zones can be planned.

4.2. Vertical aeration

Vertical aeration in landfills is a technique that involves the creation of vertical channels or wells within the waste to introduce air, promoting aerobic decomposition of organic materials (Ke et al., 2023). Waste management professionals typically bore or dig vertical wells or slots throughout the landfill layers, equipping these channels with perforated pipes that serve as conduits for vertical air distribution. Air is either blown or pumped into these pipes, allowing it to flow downward and permeate the waste layers, delivering oxygen to the aerobic microorganisms in the landfill. This influx of oxygen fosters the growth and activity of aerobic bacteria and fungi, which efficiently break down organic waste through aerobic processes, producing carbon dioxide and water instead of methane.

The advantages of vertical aeration are numerous. It provides thorough aeration throughout the landfill's depth, reaching even the most compacted and deepest waste layers where horizontal methods may be less effective. This is particularly beneficial for older or densely packed landfills. Furthermore, vertical aeration can enhance the effectiveness of other aeration techniques or landfill gas (LFG) extraction systems, thereby accelerate waste decomposition and improve gas management (Ritzkowski et al. 2012).

Careful planning of the spacing, depth, and arrangement of vertical wells or slots is essential to guarantee uniform air distribution and effective aeration across the landfill. Implementing monitoring systems to track oxygen levels, temperature, and gas emissions within the landfill enables operators to fine-tune the aeration process as required. Regular maintenance and inspections are imperative to promptly identify and rectify issues like well blockages, settling, or gas seepage that could compromise the system's performance or the landfill's structural integrity.

In summary, this method provides more uniform gas migration,

reducing methane accumulation and enhancing biodegradation by ensuring a better oxygen supply. It has a low risk of anaerobic pockets as oxygen reaches deeper waste layers. However, it is the most expensive option due to the need for deep drilling and energy-intensive air injection. Despite these challenges, it offers the best overall performance in gas control and waste degradation, making it suitable for deep landfills requiring focused aeration.

4.3. Leachate collection systems

In landfill aeration, the leachate collection system (LCS) can be repurposed to facilitate air injection, offering a cost-effective and energy-efficient alternative to traditional aeration methods such as air injection wells. Typically, LCS consist of perforated pipes installed at the base of the landfill to collect and drain leachate. By inserting aeration tubes into these pipes and connecting them to blowers, air can be distributed throughout the landfill, promoting aerobic conditions that accelerate waste decomposition and reduce methane emissions.

Song et al. (2023) investigated aerobic treatment at a closed landfill in Gyeonggi-do, South Korea (44,900 m^2, 671,000 m^3 capacity) using existing 300 mm leachate collection and drainage pipes for aeration. An aeration tube was inserted into the drainage pipe, with an air amplifier placed between the blower and tube, injecting air at approximately 5 m^3/min. This method proved more cost-effective than air injection wells, reducing energy consumption by at least 90 % and achieving an air amplification effect of 3.5 times. Gas composition analysis, CH_4/CO_2 ratio (0.06–0.25), and CH_4 emissions (~90.3% reduction) confirmed effective aerobic conditions and high GHG reduction efficiency. Bartholameuz and Hettiaratchi (2016) utilized the existing leachate collection piping system as an air distribution system in a lysimeter experiment. The experiment, which involved bubbling air through the LCS, demonstrated the potential for air to channel through the system. This channeling effect may be more pronounced in older landfills with pre-existing channels. During aeration, air was bubbled through the leachate within the gravel layer at the lysimeter's base. To prevent air circulation toward the leachate pump, the LCS was sealed during the process. From an aeration standpoint, using the LCS may promote flow channeling, making this configuration less advisable.

In summary, this method relies on existing leachate collection pipes to introduce oxygen, but it has the least effectiveness due to inconsistent oxygen distribution and channelling. It has a high risk of anaerobic pockets, as certain areas remain oxygen-deficient. While it is the least expensive method, operational challenges include leachate clogging, biofilm formation, and limited oxygen solubility. It performs poorly compared to the other two methods and could be useful for bioreactor landfills with oxygenated leachate recirculation.

5. Effects of aeration on landfill performance

5.1. Effect of aeration on leachate ammonia nitrogen

Aeration in an aerobic landfill highly affects the ammonia nitrogen (NH_3-N) content in the leachate. When air is introduced into the landfill, it promotes the growth and activity of aerobic microorganisms, which play a crucial role in nitrification. During this process, NH_3-N is oxidized to nitrate NO_3^- via intermediate nitrite NO_2^- forms. This conversion reduces ammonia nitrogen levels in the leachate, as it is transformed into less harmful forms of nitrogen. Additionally, the increased oxygen availability helps maintain more stable and efficient microbial processes, thereby improving the overall quality of leachate and reducing its potential environmental impact. Bilgili et al. (2007) noted that aeration at 0.084–0.086 L/(min·kg) of waste significantly reduces leachate ammonia nitrogen levels, with aerobic reactors showing concentrations as low as 120–200 mg/L by day 250, compared to 1800–1900 mg/L in anaerobic reactors, due to enhanced nitrification processes.

Wu et al. (2014) investigated the effect of aeration modes on the leachate properties of the landfill. Aeration at the bottom layer ensured high oxygen levels throughout the waste, as demonstrated in the pilot scale experiments for scavenging, accelerating degradation of organic carbon, and leading to lowered organic carbon content in the leachate. In contrast, aeration at the surface or middle layers less impacted organic carbon decomposition. Regarding nitrogen transformation, high air injection rates significantly reduced NH_4^+-N and T-N concentrations. Aeration at the bottom layer proved most effective for organic carbon decomposition compared to surface or middle layer aeration. The air injection rate influenced nitrogen transformation differently than organic carbon decomposition. Increasing the air injecting rate (1.0 L/min) facilitated simultaneous nitrification and denitrification, but a lower flow rate (0.5 L/min) led to sequenced nitrification and denitrification. In general, we can say that aeration of the lowest stratum close to the leachate collection pipe at a higher air injection rate improved landfill waste stabilization by promoting denitrification and organic carbon decomposition (Wu et al., 2014).

5.2. Effect of aeration on leachate COD

Aeration in an aerobic landfill plays a crucial role in reducing the COD of leachate. By introducing oxygen into the landfill, aerobic microorganisms are activated to break down organic matter more efficiently. This enhanced microbial activity accelerates the decomposition of complex organic compounds into simpler substances, which reduces the organic load and, consequently, the COD of the leachate. As a result, the oxygen demand declines due to the reduced presence of organic pollutants requiring oxidation. This process not only improves leachate quality but also makes waste management in the landfill more efficient, leading to a more stable and eco-friendly waste disposal system.

The degradation of waste organic matter can be characterized as an apparent first-order process, leading to the generation and removal of leachate COD (Cruz and de la Barlaz, 2010). Leachate COD typically peaks (COD_{peak}) shortly after the onset of MSW degradation and then decreases, generally following first-order kinetics (Grossule et al., 2018; Morello et al., 2017). Morello et al. (2017) used the rate of COD reduction to compare aerobic and anaerobic waste degradation, finding that a higher overall waste degradation rate corresponds to a faster COD decrease rate (Altouqi, 2012). Similarly, Ma et al. (2021) demonstrated that the time-dependent changes in leachate COD reflect the waste degradation process. The typical temporal pattern of leachate COD reflects two linked processes: an initial release of soluble organics to leachate (driven by hydrolysis and dissolution of labile waste fractions), which produces a COD peak, followed by biological consumption (mineralization) of those dissolved organics. The decline in the labile COD fraction after the peak is commonly approximated by a first-order decay (exponential) model (Ma et al., 2021; Contrera et al., 2014):

$$COD_t = COD_{peak} \times e_0^{)kCOD \times (t-t} \quad (1)$$

Where COD_t is the time-dependent COD value (mg L^{-1}), t is elapsed time (d), t_0 is the time to reach COD_{peak} (d), and k_{COD} is the 1st order COD removal rate coefficient (d^{-1})

This formulation is widely used in landfill and leachate studies because microbial degradation of a relatively homogeneous labile pool often follows pseudo-first-order kinetics when substrate concentration is not limiting. This approach allowed the researchers to quantitatively compare degradation rates across different aeration conditions and identify optimal aeration regimes. Based on the analysis in Ma et al. (2021), clear differences in degradation performance were observed between aerobic, anaerobic, and semi-aerobic landfill systems, as quantified by the first-order COD removal rate coefficient (k_{COD}). The average values were 0.019 ± 0.015 d^{-1} (anaerobic), 0.020 ± 0.009 d^{-1} (semi-aerobic), and 0.033 ± 0.031 d^{-1} (aerobic). Clearly it is evident that aerobic systems exhibited the highest average k_{COD}, indicating the

fastest waste degradation while semi-aerobic systems showed only marginal improvement over anaerobic systems. Besides, studies indicate that anaerobic waste degradation typically proceeds more slowly than aerobic degradation (Grossule et al., 2018; Raga and Cossu, 2013).

Ma et al. (2021) investigated the effect of the aeration rate on the aerobic degradation of MSW and reported that the aeration rate exhibited the strongest association with k_{COD} in the principal component analysis, compared with all other factors examined, including liquid recirculation, special liquid addition, waste total density, waste degradation level, and initial waste temperature, reflecting faster mineralization. k_{COD} was used to measure MSW degradation. Aerobic tests were divided into five groups based on aeration rates: less than 0.02, 0.02–0.1, 0.1–0.3, 0.3–1, and more than 1 L min^{-1} kg^{-1} DOM. The study found that increasing the aeration rate initially increased k_{COD}, which was followed by a decrease. The most significant enhancement in k_{COD} occurred at aeration rates between 0.1 and 0.3 L min^{-1} kg^{-1} DOM. Aeration rates below 0.1 L min^{-1} kg^{-1} DOM did not lead to a significant improvement in k_{COD}, likely because they were below the actual oxygen consumption rates. On the other hand, aeration rates above 0.3 L min^{-1} kg^{-1} DOM lowered k_{COD}, probably because too much water evaporated and the ventilation caused cooling. The advantages of aerobic conditions are clearly reflected in the enhanced removal of chemical oxygen demand (COD), which has an average removal rate of 0.051 d^{-1} (Grossule et al., 2018). Hybrid and semi-aerobic bioreactors exhibit performance levels that fall between anaerobic and aerobic conditions, with average removal rates of 0.0221 d^{-1} and 0.0139 d^{-1}, respectively. By analyzing the average COD removal rates, it is possible to estimate and compare the stabilization times for each type of bioreactor. The findings revealed that the time required to achieve a 95 % reduction in contaminants under aerobic conditions was significantly less than the time needed for hybrid, semi-aerobic, and anaerobic conditions, which increased by factors of 2.3, 3.7, and 6.2, respectively. These results suggest quicker stabilization correlates with shorter aftercare periods and reduced post-closure maintenance costs.

5.3. Effect of aeration on waste settlement

One of the most important parameters for evaluating the stabilization of MSW in landfill sites is waste settlement, which may depend on waste type, humidity, method of landfilling or even waste compression. Aeration in an aerobic landfill significantly influences waste settlement by speeding up the decomposition of organic materials. The introduction of air boosts microbial activity, which enhances the breakdown of organic waste into simpler compounds, leading to a significant reduction in the volume of the waste. As organic matter decomposes, it compacts and settles more rapidly, reducing the landfill's overall volume more quickly compared to anaerobic conditions. This accelerated settlement helps optimize landfill space and can reduce the need for frequent cover material applications.

Falamaki et al. (2019) examined waste settlement over a period of 200 days for both blank and aerated samples. Initially, both samples exhibited almost identical settlements during the first week. However, as time progressed, the aerated waste settled more rapidly than the blank sample, though both continued to settle at an increasing rate. This accelerated settlement in the aerated sample is due to enhanced waste decomposition prompted by aeration. Giannis et al. (2008) observed a 26 % settlement in an aerated bioreactor over 510 days, which was attributed to organic material biodegradation. Erses et al. (2008) noted 37 % settlement in 374 days for an aerated bioreactor, compared to 5 % for an anaerobic bioreactor over 630 days. Ritzkowski et al. (2012) also reported higher settlement rates near aeration equipment due to increased degradation under aerobic conditions. The plot (Fig. 6) summarizes published results spanning ~150–560 days and ~20–63.5 % settlement for reactor volumes ranging roughly from 10 to 343 L, illustrating the variability of settlement outcomes across different experimental studies. The legend shows what bubble sizes correspond to 20 L, 100 L, and 300 L, for visual interpretation of the reactor volumes.

Ko et al. (2016) observed initial settlement across all bioreactors was around 5 % over the first 10 days due to waste weight and compressive forces. At the end of the experiment, the highest settlement of 25.7 % was observed in the aerobic reactor with a 30/L air flow rate having four times per day aeration frequency for 2 h. Settlement in aerobic reactor closely matched organic carbon reduction, like BOD_5, with significant drops at days 21 and 138 for settlement and days 23 and 133 for BOD_5 reduction. Settlement in aerated waste seems influenced by both organic decomposition and degradation rate. Differences in moisture content, affected by aeration levels, might also impact settlement. Higher aeration rates, while removing more moisture, could lead to drying and subsequent shrinkage in MSW.

Overall, the degree of waste settlement increased with higher aeration rates, demonstrating that aeration can effectively accelerate waste stabilization. Given the costs associated with aerating MSW landfills, it is recommended that landfill operators use a low daily aeration frequency if the goal is to reduce organic carbon content and total nitrogen in the leachate. However, high daily aeration can lead to substantial space gain and rapid nitrogen removal. An overview of experimental

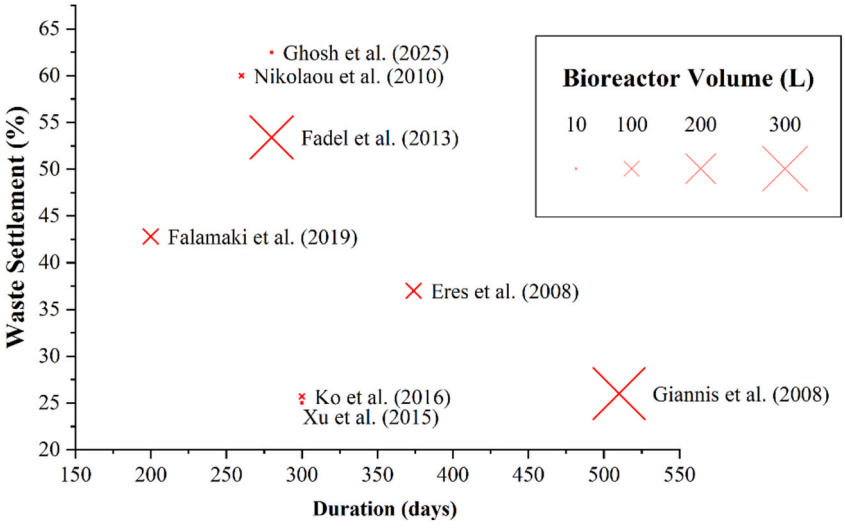


Fig. 6. Reported waste settlement (%) plotted against operation duration (days) from selected literature. Each labeled marker identifies a study (author, year); marker size encodes bioreactor volume (L) as shown in the inset legend.

conditions and results in ABRL studies is summarized in Table 3.

5.4. Off-gas composition

The primary component of off-gas in an aerobic system is CO_2, which results from the aerobic microbial degradation of organic waste. O_2 is also present in the off-gas, reflecting the ongoing supply of air to support aerobic conditions. Because CH_4 is not a product of aerobic decomposition, levels are much lower than in anaerobic landfills. The off-gas may also contain trace amounts of other gases such as nitrogen (N_2), water vapor, and potentially some VOCs, although these are typically in smaller concentrations. The enhanced degradation process in aerobic conditions leads to more efficient waste stabilization and a reduced risk of harmful GHG emissions. In lab-scale tests, off-gases typically comprise 10–20 % oxygen and 0–20 % carbon dioxide. Under aerobic conditions, methane generation is nearly entirely inhibited, with CO_2 being the primary product (Slezak et al., 2015). Although aerobic conditions hinder energy recovery, they help mitigate environmental impacts when biogas collection and control are not technically or economically feasible and when uncontrolled emissions are expected. Ritzkowski and Stegmann (2007) showed that in situ aeration could reduce over 72 % of greenhouse gas emissions typically produced under anaerobic conditions. Slezak et al. analyzed CO_2 and CH_4 emissions from anaerobic and aerobic bioreactors, reporting that the carbon gas emitted from aerobic bioreactors was about five times greater than that from anaerobic bioreactors because waste stabilizes more quickly under aerobic conditions, and carbon gasification is enhanced.

Possible drawbacks that limit the use of aerobic landfill systems include the risk of waste drying out because of high temperatures. This can make it harder for temperature-sensitive biological processes to remove nitrogen and increase the risk of high temperatures or fires. However, these issues can be mitigated by controlling methane production, maintaining proper moisture content, and implementing waste pretreatment (Berge et al., 2005). High energy costs for compressed air injection can be reduced by carefully choosing operating parameters like aeration and recirculation rates to improve waste decomposition and save energy (Rich et al., 2008). A cost model created by Read et al. suggests that aerobic landfills could be cost-effective if valuable materials can be recovered from the site (Read et al., 2001a,b).

Table 3
Important findings from different lysimeter experiments under aerobic conditions.

Bioreactor Volume (L)	Number of bioreactors	Temperature (°C)	Packing density (kg/m^3)	Moisture content (%)	Aeration rate (l/min.kg)	Duration (days)	Leachate COD removal	Reference
10	3	22	650	50.5	0.1	280	t_0 = 1500 85 %	Ghosh et al. (2025)
6.88	3	36 ± 1	620–730	55.58	0.0047–0.0057	448	t_0 = 27,500 95 %	Sohoo et al. (2021)
6.18	4	25 ± 5	800	NR[a]	0.032	105	t_0 = 5627 50.4 %	Chu et al. (2021)
98	2	20	402	57.6	0.397	200	similar initial and final COD	Falamaki et al. (2019)
63.5	5	29–31	450–650	NR[a]	0.303–0.437	200	t_0~42,500 97.6 %	Qiu et al. (2020)
12.37	6	30 ± 5	500	54.3	0.026–0.08	242	NR[a]	Nag et al. (2018)
14	3	25–30	840	NR[a]	0.0002–0.0008	256	t_0 ~1800 > 98 %	Li et al. (2018)
12	6	38–40	384	NR[a]	0.005–0.027	573	t_0~100,000 > 99 %	Morello et al. (2017)
1407	3	29–38	581–635	60–70	0.014–0.021	250	t_0 ~82,500 93.9 %	Yazici Guvenc et al. (2017)
31.4	4	30 ± 5	600	49.7 %	0.009–0.037	300	t_0 = 60,000 96 %	Ko et al. (2016)
250	3	25–30	550	60–65	0.123	160	t_0 = 44,800 91 %	Ahmadifar et al. (2016)
4.7	3	30 ± 2	640	44	0.028–0.045	130	t_0 = 50,000 80 %	Xu et al. (2016)
47.9	6	39–42	500	55–60	0.001	100	t_0 = 50,000 66.3 %	Cossu et al. (2016)
20	3	35 ± 2	250–300	50	1.417	180	t_0 = 5350 97.1 %	Bolyard and Reinhart (2016)
15	2	NR[a]	560	53.4	4.41 × 10^{-3}	196	t_0 = 40,000 87.5 %	Slezak et al. (2015)
15.7	4	35–55	655	NR[a]	0.016	396	t_0 = 4750 91.5 %	Tong et al. (2015)
11.5	3	30	570	42.4	0.028–0.057	300	t_0 = 80,000 91.2 %	Xu et al. (2015)
282.7	3	35	657–875	72	0.055–0.074	280	t_0 = 95,600 90 %	Fadel et al. (2013)
47.9	6	45	970–990	38–49.9	0.0001	180	t_0 = 2000 90 %	Raga and Cossu (2013)
89.2	2	30	665	63.7	0.002	262	NR[a]	Sun et al. (2013)
392.6	4	NR[a]	519–537	25	0.051–0.052	250	t_0 = 50,000 89.7 %	Bilgili et al. (2012)
2.35	5	35 ± 5	550–610	58.8	0.007–0.011	80	t_0 = 3320 63.8 %	He et al. (2011)
25	4	22 ± 2	600	NR[a]	0.2	260	t_0 = 44,000 93.2 %	Nikolaou et al. (2010)
96	2	32	203	NR[a]	0.1128	374	t_0 = 19,237; 96.4 %	Eres et al. (2008)
343	1	15	628	40–50	0.2647	510	t_0 = 4150; 91.5 %	Giannis et al. (2008)

[a] NR = not reported; 't_0'=initial COD (mg/L); '%' = COD removal efficiency.

6. Leachate recirculation systems

6.1. Leachate recirculation technique

Leachate is recirculated in a landfill to enhance the moisture content of MSW and to facilitate the distribution of microbes and nutrients, thereby accelerating the biodegradation process of the MSW. Leachate injection is achieved through the installation of a dedicated recirculation system within the landfill. In engineering practice, surface spraying, vertical wells, and horizontal trenches are the most prevalent leachate recirculation systems (Fig. 7) employed in landfills (Zhang et al., 2021).

6.1.1. Horizontal trenches

A typical horizontal trench is constructed by excavating a specific size (typically 0.6 m × 0.6m) and length of the trench at the desired depth and location within the MSW mass (Reddy et al., 2017). A trench is then dug, and a perforated pipe is installed inside this trench. According to Haydar and Khire (2005), these dimensions were chosen based on common designs of existing landfills that were in operation. They filled the trench with highly permeable materials like gravel shards, tires, and recycled glass. Leachate is introduced into the horizontal trench system based on the required flow per unit length of the trench over a unit time.

Reddy et al. (2010) tested four designs for horizontal trenches (HTs) with different spacing setups. They found that the best design, called HT-C4, had a horizontal spacing of 30 m and a vertical spacing of 6 m. This setup achieved even leachate distribution within two weeks of injection. However, the study showed that continuous leachate injection caused pore water pressure to rise significantly, with HT-C4 reaching up to 250 kPa after four weeks. This could lead to stability problems in the landfill. Injecting leachate into horizontal trench (HT) systems near landfill side slopes can pose a risk to slope stability. This happens because excess fluid (water and gas) pressures can build up, reducing the strength of the waste material by lowering the effective stress, which might cause the slope to become unstable. There have been cases of landfill slope failures linked to high pore pressures near the side slopes (Thiel and Christie, 2005). Using intermittent injection, such as injecting for one week and stopping for the next, helped lower moisture levels to 60–80 % and reduced pore water pressures compared to continuous injection. The study also tried injecting leachate into alternate HT layers, improving moisture distribution and reducing pore water pressures. This setup created moisture levels that supported better waste breakdown. The results suggest that a staggered HT design with intermittent injection is a better way to manage moisture and pressure, improving waste degradation in landfills.

Currently, there is no clear guideline on the minimum safe distance between horizontal trenches and side slopes. It is crucial to consider the buildup of water and gas pressures when assessing the stability of landfill slopes. A well-designed leachate recirculation system should distribute moisture effectively without causing high pore pressures. Horizontal trenches are commonly used in new landfills and are usually installed as the waste is being placed.

In summary, this technique improves leachate distribution by targeting specific horizontal layers, allowing for moderate landfill stabilization. It is more effective in gas management than surface spraying, as it helps reduce pore gas pressure. Settlement occurs at a moderate rate, improving waste saturation. While this method is more efficient at removing VFAs than surface spraying, it is still limited to horizontal layers, making it less effective in very deep landfills.

6.1.2. Vertical wells

Vertical wells (VWs) resemble gas extraction wells and serve as straightforward structures for injecting leachate into landfills, with potential for post-recirculation extraction of LFG. VWs typically range in diameter from 0.3 to 1.2 m and may feature screening either throughout their entire depth or at specific intervals. A key advantage of VWs is their versatility, allowing installation in closed and active landfills. While certain regions, especially tropical areas, may harbor waste with high initial moisture content due to organic composition, climate, and inadequate landfilling practices, waste in many global regions remains unsaturated before leachate addition. Upon leachate injection, the waste transitions from an unsaturated to a saturated state. VWs are frequently utilized in landfills when installing horizontal trenches is either unfeasible or not cost-effective (Kulkarni, 2012; Feng et al., 2017). However, employing VW recirculation may not prove effective, as gravity can lead the recirculated leachate to descend directly toward the leachate collection systems situated at the landfill's base.

Consequently, a significant portion of the leachate remains underutilized for thoroughly moistening dry zones. One proposed solution to mitigate this issue involves facilitating the horizontal flow of the leachate by integrating combined spraying-VW systems. This approach allows the leachate to traverse through a greater volume of MSW, thereby enhancing its distribution and utilization.

In summary, this is the most efficient method for leachate recirculation, providing uniform vertical infiltration and targeting deeper waste layers. It promotes rapid landfill stabilization and effectively mitigates gas pressure during landfill gas generation. The settlement rate is the fastest, which may require additional infrastructure reinforcement to prevent structural issues. It also offers the best removal of VFAs, contributing to efficient landfill stabilization. However, it has high capital and operational costs, making it a costly option. It is most suitable for deep landfills requiring advanced gas and leachate management.

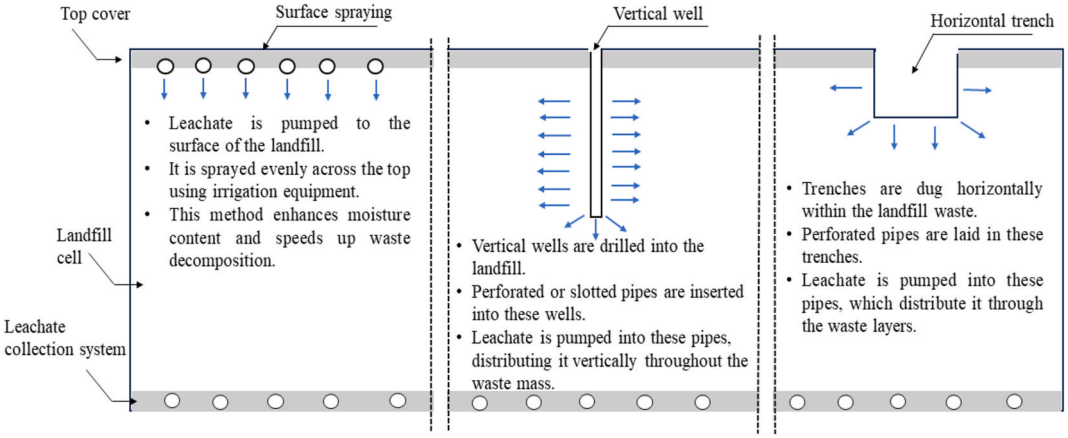


Fig. 7. Hypothetical representation of bioreactor landfill cells using different leachate recirculation systems (Modified after Zhang et al., 2021).

6.1.3. Surface spraying

In this method, leachate is sprayed evenly across the waste surface using nozzles that create mist or fine droplets. Leachate from the storage tank is transferred to the spraying equipment or spray nozzles distributed across the landfill surface to ensure even leachate distribution. The nozzles spray the leachate over the landfill surface in a controlled manner, ensuring even distribution. The spray pattern and intensity can be adjusted based on landfill conditions and operational goals. A piping system connects the storage tank to the spray nozzles, often laid out across the surface of the landfill. The nozzles spray the leachate over the landfill surface in a controlled manner, ensuring even distribution. Most operations are carried out using large spray guns designed to effectively redistribute leachate across the waste surface. Typically, Hypro™ spray nozzles with a 10 mm diameter were employed to achieve uniform coverage and controlled droplet dispersion (Gray et al., 2005). The spray pattern and intensity can be adjusted based on landfill conditions and operational goals. By maintaining optimal moisture levels, surface spraying accelerates the decomposition of organic waste. The application rates can vary depending on site conditions, but they are generally maintained at approximately 50 m^3 per hectare per day, ensuring adequate moisture distribution to enhance waste degradation.

Leachate spraying is highly flexible, with systems designed for easy relocation to different areas to optimize application rates and avoid active zones. This method offers a significant potential for volume reduction (Reinhart et al. 1996). However, spraying cannot be performed during rainy or freezing conditions and is incompatible with using an impermeable cover upon closure. Besides, spraying leachate on the surface can release unpleasant odors. Proper management and timing of spraying (e.g., during periods of low wind) can mitigate this issue.

In summary, this method has limited control over leachate infiltration, leading to uneven distribution. As a result, landfill stabilization is slow, and gas release is inconsistent due to inefficient leachate percolation. Settlement occurs at a slow rate because the leachate remains at the surface, reducing its interaction with deeper waste layers. It has low capital and operational costs, making it an economical choice for small landfills. However, it is ineffective for deep or compacted waste layers and results in uneven moisture distribution.

6.2. Leachate recirculation approaches

6.2.1. Conventional leachate recirculation

Leachate recirculation effectively reduces the amount of leachate released in aerobic and anaerobic landfills (Bilgili et al., 2006). Particularly in aerobic landfills employing leachate recirculation, the emission levels for leachate are notably minimized, featuring low COD, ammonia, and TKN concentrations. Research, such as that conducted by Tong et al. (2015), illustrates the positive impact of leachate recirculation on the hydrolysis of organic matter, particularly food waste. This intervention fosters increased interaction between hydrolytic bacteria and solid surfaces, addressing the rate-limiting step of hydrolytic acidification in the degradation of bulky organic materials (Vavilin et al., 2010).

Various studies have highlighted leachate recirculation as a pivotal factor in enhancing hydrolysis and acid production efficiency, improving solid-phase solubility, and promoting mass transfer processes. These findings collectively underscore the significance of leachate recirculation in landfill management, emphasizing its role in optimizing waste degradation and mitigating environmental impacts (Zhang et al., 2022). However, excessive saturation of leachate could counteract the advantages of aeration, as highlighted in studies by Hrad and Huber-Humer (2017) and Raga and Cossu (2014). Research like that by Yazdani et al. (2010) has demonstrated a notable rise in anaerobic activity with leachate recirculation in aerobic landfills. Moreover, elevated levels of leachate can accelerate leachate seepage and compromise the physical stability of waste masses, potentially causing landfill instability and slides, as highlighted in studies by Grossule et al. (2018), Zhan et al. (2017), and Zhang et al. (2018). However, it is crucial to recognize that leachate recirculation also increases initial investment and ongoing management costs, as Grossule et al. (2018) emphasized. As a result, there is a consensus against excessive leachate or water recirculation in aerobic landfill systems.

6.2.2. Leachate recirculation with micro aeration/oxygenation

Leachate recirculation is a vital strategy in landfill management, as recent studies indicate. This approach offers multifaceted benefits, including a significant reduction in leachate volume requiring treatment, augmentation of water content, and the redistribution of crucial nutrients and microorganisms within the landfill strata (Xu and Zhang, 2022). Waste decomposition and stabilization processes are notably expedited by reintroducing leachate into the landfill core, concurrently enhancing LFG production and facilitating settling (Tong et al., 2015).

Liu et al. (2023) highlighted the potential benefits of combining micro-aeration and leachate recirculation to speed up the stabilization of landfill waste. It highlights the challenges municipalities face in managing landfill waste and the need for faster stabilization methods to reduce environmental impact. The study demonstrates that combining micro-aeration and leachate recirculation significantly enhances the degradation of organic matter in landfill waste. The study shows that using micro-aeration and leachate recirculation together greatly improves the breakdown of organic matter in landfill waste. With this method, the removal rates of COD, TP, and NH_4^+-N were 80.17 %, 48.30 %, and 48.56 %, respectively, and the rate of organic matter breakdown reached 50 % (Liu et al., 2023). The results indicate that the integrated approach leads to an increased removal of COD, TP, and NH_4^+-N, as well as a higher organic matter degradation rate.

The study on pure oxygen leachate recirculation highlights its significant impact on landfill performance, particularly in enhancing MSW stabilization (Ghosh et al., 2025). The bioreactor R1, which utilized oxygenated leachate recirculation, achieved approximately 85 % COD removal efficiency, largely due to the high dissolved oxygen (DO) levels maintained during the process. This method also resulted in a remarkable 99 % removal efficiency of ammonia nitrogen through rapid aerobic nitrification, demonstrating the effectiveness of oxygenation in promoting microbial activity. In comparison to conventional leachate recirculation (R2) and anaerobic control (R3), R1 exhibited superior waste settlement, achieving a cumulative subsidence height of approximately 63.5 % after 280 days of reactor operation. The oxygenated leachate not only accelerated the degradation of organic materials but also improved leachate quality. Furthermore, the introduction of pure oxygen into the leachate significantly enhanced the overall microbial community structure, with Proteobacteria being the dominant phylum, which is crucial for the degradation of organic compounds.

The findings suggest that oxygenated leachate recirculation is a promising strategy for optimizing landfill management, reducing environmental impacts, and improving the efficiency of waste stabilization processes.

6.2.3. Leachate recirculation with H_2O_2 pretreatment

Huang et al. (2012) studied treating MSW by modifying and recirculating leachate in a simulated landfill bioreactor. Their findings revealed that adding hydrogen peroxide to the recirculated leachate significantly increased dissolved oxygen levels, enhancing the biodegradation of organic matter. Over a 405-day period, the biochemical oxygen demand (BOD_5) in the collected leachate decreased by 99.7 %, while chemical oxygen demand (COD) was reduced by 96 %. This process substantially accelerated organic carbon degradation, allowing the landfill to reach a stable state more quickly.

The study also indicated that the continuous addition of hydrogen peroxide to the leachate system resulted in a faster biodegradation rate compared to recirculation alone, with continuous application proving more effective than intermittent addition. It was observed that biodegradation approached stability when the BOD_5/COD ratio fell below 0.2

and when carbon dioxide concentrations surpassed methane concentrations during the stable phase. These findings suggest that enhancing leachate recirculation with hydrogen peroxide could be a valuable strategy for accelerating the biodegradation of MSW in landfill bioreactors, thereby shortening operational timelines and reducing pollution monitoring costs.

7. Challenges in aerobic landfill techniques

Aerobic landfill techniques, while promising for sustainable waste management, come with several significant challenges that must be addressed to ensure their effective implementation and operation.

- **Oxygen Diffusion and Distribution**: One of the primary challenges in aerobic landfilling is ensuring sufficient oxygen reaches all parts of the landfill mass. This requires effective aeration systems that uniformly deliver oxygen throughout the waste matrix. Achieving adequate oxygen diffusion can be challenging due to the heterogeneous nature of waste materials and varying degrees of compaction within the landfill.
- **Moisture Management**: Proper moisture content is crucial for aerobic decomposition. Excess moisture can create anaerobic pockets within the landfill, reducing oxygen availability and promoting the generation of methane and other anaerobic by-products. Conversely, insufficient moisture can limit microbial activity and slow down waste degradation. Managing moisture levels through effective leachate recirculation systems and waste cover materials is essential but can be technically demanding.
- **Energy and Operational Costs**: Aerobic landfill systems require significant energy inputs for aeration, leachate recirculation, and gas management systems. High operational costs, including maintenance and monitoring expenses, can be prohibitive and impact the economic viability of aerobic landfilling as compared to traditional landfill practices.

Technological advances, such as automated monitoring systems and improved aeration techniques, and innovative waste management strategies, are crucial for overcoming these obstacles and realizing the full potential of aerobic landfill techniques in sustainable solid waste management.

8. Worldwide case studies in the last decade

8.1. China

Liu et al. (2018) studied how to optimize in situ aeration in an old landfill in China using a MWOAM. The goal was to boost aerobic degradation by adding more air to the landfill and improving oxygen levels. The main objective is to enhance aerobic degradation by transporting additional air into landfills and creating an improved oxygen environment. The MWOAM selects the WS and aeration rate based on gas transport properties, with the key objective being to maximize the OSR. This method was successfully used in the aeration restoration project at the Jinkou landfill. It showed that providing enough oxygen throughout the landfill and running the aeration system for a long time was adequate. The optimization program is structured to provide oxygen movement in the target landfill, calculate the objective function of OSR, select WS and AR using optimization theory and neural networks, and perform reliability analysis. The optimization model considers factors such as gas transport, heat release from an aerobic reaction, and the final cover of the waste body to optimize the oxygen concentration in the extraction well. The results of the optimization program include the selection of WS and gas flux of a single well, which were implemented in the Jinkou landfill restoration project. Applying the MWOAM in the Jinkou landfill resulted in a significant increase in OSR during the aeration period, indicating sufficient oxygen supply to enhance the aerobic environment. The variation of oxygen and methane concentrations during aeration showed favorable effectiveness in restoration, and the temperature in the landfill body remained within the optimal range for aerobic biodegradation. In conclusion, the MWOAM effectively improves aeration systems in large landfills, offering strong support for designing and managing these systems. The successful application in the Jinkou landfill demonstrates the potential of this method to improve the degradation efficiency and ensure continued aeration in long-term landfill restoration projects.

8.2. Austria

The study was conducted at an old MSW landfill in Austria, utilizing low-pressure air injection alongside simultaneous off-gas collection and treatment (Hrad et al. 2017). The old MSW landfill spanned 2.6 ha and contained approximately 200,000 metric tons of waste. An aeration system involved the injection of low-pressure air through 37 gas wells, simultaneous off-gas collection, and treatment. A comprehensive field monitoring program was implemented, which included waste and leachate sampling, gas quality analysis, and temperature monitoring to evaluate the impact of aeration. The effectiveness of low-pressure aeration was assessed in terms of accelerating organic matter degradation, improving leachate quality, and reducing LFG emissions. The aeration measure significantly reduced biological reactivity parameters (RA_4 and GP_{21}) and ammonium-nitrogen (NH_4^+-N) concentrations in the leachate, indicating improved waste stability. However, the impact was less pronounced compared to other aeration projects, likely due to technical limitations in air distribution. The field application of aeration resulted in lower carbon discharge via the gas phase than laboratory-based predictions. This discrepancy was attributed to technical challenges such as high air flow resistivity caused by the high-water content of the waste and temporarily elevated water levels within the landfill. There was no significant improvement in organic leachate compounds (BOD_5 and COD) during the aeration period. However, a decreasing trend in NH_4^+-N and COD concentrations was observed after the completion of aeration, suggesting a potential long-term benefit of the aeration process. The study highlights the potential of in-situ aeration to significantly enhance the stability of old MSW landfills and reduce their emission potential. Nevertheless, it also underscores the challenges associated with effective air distribution and the limitations posed by the initial stability of the waste material. The findings indicate that while aeration can lead to short-term improvements in waste stability and leachate quality, long-term benefits may be more pronounced following the cessation of aeration measures.

8.3. Turkey

Top et al. (2019) shared the results of a field-scale study using test cells to examine how aeration and leachate recirculation affect waste decomposition, solid waste properties, landfill gas (LFG) composition, and settlement in landfills. Four test cells, each measuring 20 m × 40 m x 5 m, were built at the Komurcuoda Sanitary Landfill in Istanbul. The study looked at ways to speed up the stabilization of solid waste by analyzing its properties (such as pH, moisture, TOC, TKN, C/N ratio, volatile solids, and more), LFG components (like CH_4, CO_2, O_2, and H_2S), temperature changes in the landfill, and settlement. The results showed that aeration and leachate recirculation improve the biodegradation of MSW. This accelerated biodegradation significantly reduces the pollutant lifespan in the landfill, achieving substantial waste volume reduction in a shorter period compared to anaerobic test cells. Consequently, this reduces the costs associated with long-term monitoring after landfill closure.

In summary, the study concludes that aeration in MSW landfills is an effective management strategy for accelerating the stabilization of the waste matrix. Aerobic test cells demonstrate a higher biodegradation rate and achieve greater waste volume reduction in a shorter time than

anaerobic cells. This accelerated biodegradation decreases the operational lifespan of the landfill and reduces overall post-closure monitoring costs.

8.4. South Korea

In a landmark development for landfill management in South Korea, the Seoul Metropolitan Landfill Management Corporation, under the Ministry of Environment, has introduced the nation's first leachate recirculation system, at the second metropolitan landfill site as reported by the local media (e-Newsp, 2025) This facility, aligned with the U.S. EPA defined bioreactor landfill concept, began full-scale operation on June 30, 2020 and is capable of recirculating up to 3200 tons of leachate daily into 8 of the 24 landfill blocks. Future expansion plans include a second-phase system with a capacity of 2600 tons/day to cover the remaining blocks, ultimately forming a zero-discharge leachate management system. The facility employs a dual-pipe network for simultaneous leachate injection and landfill gas (LFG) capture, effectively increasing in-situ moisture content from 26 % to potentially 40 %. This enhanced moisture accelerates decomposition of organic waste, significantly reducing the post-closure management period and saving an estimated KRW 101.5 billion in long-term monitoring costs. Additionally, improved LFG recovery is projected to support power generation at a 50 MW facility, yielding up to KRW 78.8 billion in energy value. The system also helps reduce GHG and odorous gas emissions, supporting broader goals of transforming the landfill into a site with no leachate discharge, no dust, and no odor while advancing sustainable, low-carbon waste management practices in South Korea. Likewise, Sim et al. (2018) reported the installation of a leachate recirculation system at the Sudokwon landfill in Incheon to maintain internal moisture and prevent the drying up of waste. From October 2013 to July 2016, recirculating 137,362 m^3 of leachate in Block 3C of Cell 2 at the Sudokwon landfill, Incheon, raised waste moisture from 36.5 % to 37.8 % (versus a drop from 27.7 % to 22.6 % in the control), directly counteracting landfill drying. This moisture enhancement resulted into a 71 % higher net methane collection rate 12.5 m^3/min versus a 7.3 m^3/min without recirculation. Overall, leachate recirculation effectively accelerates organic decomposition, enhances gas yields, and improves the economics and stabilization timeline of landfill operations.

9. Recommendations for field application and further research

In conclusion, aerobic bioreactor landfills (ABRLs) accelerate waste stabilization and significantly reduce methane emissions relative to conventional anaerobic landfilling when operated under controlled conditions (e.g., maintained moisture ~40–70 % wet basis and in-waste O_2 levels achievable at or above ≈5 % where feasible). Although ABRLs incur higher capital and operational costs (aeration systems, energy demand, and intensified monitoring), these are commonly offset by shorter aftercare periods, lower long-term leachate treatment burdens, reduced environmental liabilities, and earlier land reuse. The success of pilot projects in countries like the United States, and within the EU serves as a model for broader implementation, highlighting the environmental benefits and feasibility of this approach. Representative demonstrations include the Georgia test cells in the United States, which reported faster waste stabilization and reduced CH_4 emissions (Read et al., 2001a,b), the Teuftal in-situ aeration project in Europe that documented enhanced carbon mobilization and biostabilization at field scale (Ritzkowski et al., 2018), and Italian bioreactor tests that guided subsequent field aeration trials (Raga and Cossu, 2013). These case studies corroborate the environmental benefits and technical feasibility of aerobic approaches while underscoring the need for site-specific design, energy accounting and long-term monitoring. However, the net climate and economic benefits are site-dependent and therefore should be demonstrated by site-specific life cycle and cost–benefit assessments prior to full-scale adoption.

For real-world implementation, we recommend starting with small pilot cells that reflect the actual waste composition and climate of the site. These pilots should use flexible aeration systems that allow operators to adjust the aeration duty cycle. This flexibility is important because different goals may require different aeration strategies, for example, higher aeration frequencies can speed up nitrogen removal, while lower frequencies may be better for long-term carbon degradation. We also suggest installing a comprehensive monitoring system that measures gas composition (CH_4, CO_2, O_2, N_2O), leachate characteristics (COD/BOD, NH_4^+, NO_2^-, NO_3^-), and in-situ parameters (moisture, temperature, ORP). Such monitoring will support automated, closed-loop control and help manage potential problems such as odor emissions or unexpected N_2O release.

For future research, we identify four key priorities.

1. Scale-up studies that examine how well the positive results seen in laboratory experiments carry over to full-scale landfill cells under real operating conditions.
2. Systematic testing of different aeration duty cycles to better understand their effects on carbon and nitrogen removal, including the potential trade-offs related to N_2O emissions.
3. Comprehensive site-level life-cycle assessments (LCA) and cost–benefit analyses that consider energy consumption for aeration, maintenance needs, and the possible loss of landfill gas recovery.
4. Development of practical guidelines, training materials, and supportive policies, including operational standards, incentive programs, and public–private partnerships, to encourage safe, effective, and widespread adoption of aerated landfill technologies.

These actions will help ensure that ABRLs are deployed safely, cost-effectively, and with measurable environmental benefits. With coordinated pilot work, robust monitoring, and supportive policy, aerobic bioreactor technology can become a practical tool for reducing landfill emissions and recovering land for productive use. Continued collaboration between researchers, operators, and policymakers will be essential to realise this potential at scale.

CRediT authorship contribution statement

Arnab Ghosh: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Tanushree Paul:** Visualization, Validation. **Anumita Mishra:** Writing – review & editing. **Jurng-Jae Yee:** Resources, Project administration, Funding acquisition. **Sung Hyuk Park:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition.

Ethical approval

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Consent to participate

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Data availability

No data was used for the research described in the article.

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