Water Air Soil Pollut (2025) 236:147
https://doi.org/10.1007/s11270-025-07769-7

Oxygenated Leachate Recirculation for Enhanced MSW Stabilization and Landfill Space Reclamation: Lab-Scale Bioreactor Insights

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Received: 1 August 2024 / Accepted: 10 January 2025
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Abstract This study investigates aerobic landfill stabilization using three bioreactors with different operational modes: R1 with oxygenated (~90% pure oxygen) leachate recirculation and waste mass aeration, R2 with conventional leachate recirculation (without oxygenation) and waste mass aeration, and R3 as an anaerobic control. The waste stabilization was assessed by reductions in COD, ammonia nitrogen, NOx (nitrate and nitrite nitrogen), and total phosphorus removal, as well as reductions in volatile solids and subsidence of waste height. Among the three reactors, R1 exhibited the best performance, with ~85% COD removal efficiency likely due to the high DO content during leachate recirculation. Additionally, R1 achieved ~99% removal efficiency of ammonia nitrogen through rapid aerobic nitrification. An exponential attenuation model was applied to describe the degradation of organic substances, with degradation rates of COD and NH_3-N increasing from 0.005 and 0.007 d^{-1} to 0.01 and 0.021 d^{-1}, respectively, when leachate recirculation and oxygenation were applied. Reactor R1 could meet the COD emission limit of 150 mg/L, as specified by WHO surface water regulations, by day 478, while reactors R2 and R3 are expected to achieve this level by days 567 and 742, respectively. The results indicated that the aerobic conditions in R1, supplemented with pure oxygen (~90%) aeration, elicited rapid stabilization of the simulated landfill waste, reflected by a high waste settlement of ~63.5%. The findings suggest that this strategy can improve landfill stabilization in practice, optimize landfill space reuse, and enhance MSW management by reducing the load on existing leachate treatment facilities.

Keywords Municipal solid waste · Sustainable landfill · Aerobic degradation · Pure oxygen · Leachate recirculation · In-situ treatment

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1 Introduction

Sanitary landfilling remains a mainstream practice and an unavoidable final step to dispose of municipal solid waste (MSW). Even though a consistent reduction of the deposition of untreated MSW is envisaged in European policies, waste disposal in the final phase of its lifecycle will remain an important tool.

Published online: 30 January 2025

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It is impossible to have a circular economy without closing the material loop sustainably. Hoang et al. (2022) highlighted the escalating global generation of municipal solid waste (MSW), which is expected to intensify with the projected population growth, reaching a total of 10 billion people by 2057. In such scenario landfill management faces challenges such as MSW stabilization, reduction of leachate pollutants (Calabro et al. 2021), and minimization of greenhouse gas emissions. Traditional landfills have slow MSW degradation rates, requiring long periods for stabilization and maintenance. Biogas from anaerobic landfills can be used for energy generation for 10–20 years, followed by slow methane generation for several decades (Barros et al., 2018). Complete biological stabilization of an anaerobic landfill takes about 100 years (Rich et al., 2008). Globally, sustainable landfills are a key goal in waste management (Ritzkowski et al. 2012; Nag et al., 2018).

In this context, landfill aeration is regarded as a crucial technique for the controlled and sustainable transformation of traditional anaerobic landfills into biologically stable sites, which are characterized by a significant reduction in landfill gas volume or even a near-zero potential for gas emissions (Nag et al., 2018). It offers an alternative to landfill gas (LFG) energy projects by reducing long-term greenhouse gas (GHG) emissions and shortening the necessary aftercare period for landfills, especially when energy recovery is no longer economically feasible (Pivato et al., 2022; Song et al., 2023). Waste aeration reduces the pollutant loads in the leachate, as indicated by chemical and biochemical oxygen demand (BOD_5) (Erses et al., 2008; Falamaki et al., 2019; Hashisho & El-Fadel, 2014; Ma et al., 2021a, 2021b). Compared to anaerobic landfilling aerobic landfill advantages include faster stabilization, enhanced waste settling rates, lower leachate production, and better end products (Slezak et al., 2015). Besides, aerobic waste decomposition offers the benefit of reduced odor emission. Moreover, it is a growing trend to convert old landfills to aerobic operations to minimize methane emissions (Ritzkowski & Stegmann, 2012; Sutthasil et al., 2019). Despite its benefits, landfill aeration can pose economic challenges during operation due to the high-power consumption of blowers. Over the long term, continuous air injection into a landfill leads to significant operational costs (Song et al., 2023). Additionally, the air injected into the bioreactor must be tightly controlled; otherwise, uncontrolled air injection can increase temperatures, potentially causing fires and explosive accidents at the site (Ban et al., 2015; Lee et al., 2023). While landfill aeration is not yet widely practiced, it has already been successfully implemented at several landfills across Europe, North America, and Asia (Stegmann & Ritzkowski, 2007; Nag et al., 2018).

Bioreactor landfills have emerged as a promising solution to the limitations of conventional landfills by significantly reducing stabilization time, as highlighted by Morello et al. (2017), Nanda and Berruti (2021), and Chu et al. (2021). Unlike conventional landfills, which require 30 to 50 years or more to stabilize, bioreactor landfills can achieve stabilization of organic waste within 5 to 10 years by accelerating microbiological processes (Kumar et al., 2011). This acceleration is achieved by providing simultaneous moisture and air supply, which enhances microbial activity and allows for controlled methane emissions through air or oxygen injection, creating an aerobic environment that promotes biodegradation (Read et al., 2001). Compared to anaerobic methods, aerobic bioreactor landfills significantly improve the degradation of organic matter. Given the constraints on urban space, landfill reclamation and reuse have become crucial for sustainable development (Wagner & Raymond, 2015; Nanda & Berruti, 2021). The stabilization of waste in bioreactor landfills can increase landfill space by 15–30% (Wang & Wang, 2022). Recent studies have demonstrated that bioreactor landfill technology aids in the degradation and stabilization of biodegradable organic waste through techniques such as water addition, air injection, and leachate recirculation (Chu et al., 2021; Nanda & Berruti, 2021). Recently, Folino et al. (2024) analyzed the long-term effects of concentrated leachate recirculation at the Fossetto landfill in Tuscany, Italy, where reverse osmosis technology has been employed since September 2006. Their study examined the impact of recirculating treated leachate on its quality and quantity over a span of 16 years. The findings conclude that recirculation of concentrated leachate is an effective treatment approach that does not significantly increase pollutant levels in the leachate. The Metropolitan Landfill Management Corporation in Korea has launched the first phase of a landfill leachate management facility based on the bioreactor landfill concept recognized by the US EPA. Now

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in full-scale operation, the facility recirculates up to 3,200 tons of leachate daily back into the landfill, aiming to eliminate external discharge. This system benefits the environment by reducing water and ecosystem contamination, minimizing landfill gas emissions, and enhancing organic waste decomposition. Additionally, it is expected to generate power, accelerate waste decomposition, and reduce the aftercare period, leading to estimated cost savings of 76 million USD (Shim et al., 2018).

In our earlier work, we introduced a novel multistage vortex aerator (MVA) to enhance oxygen transfer rate and efficiency, developing a gas transfer model to predict its performance under various conditions (Park et al., 2022). The MVA was later used for in situ remediation of a polluted urban stream in Korea, highlighting the importance of dissolved oxygen for water quality improvement and odor mitigation (Ghosh et al., 2023). Utilizing pure oxygen amplifies the driving force for oxygen transfer, significantly increasing the potential degree of oxygen saturation due to its partial pressure being 4.7 times that of atmospheric oxygen. This results in optimized oxygen transfer rates (OTR) and sustained high dissolved oxygen (DO) levels, particularly under conditions of lower flow rates and high organic loadings (Skouteris et al., 2020). Rodríguez et al. (2013) demonstrated that pure oxygen (PO) aeration consumed less energy, with power costs being 25% lower compared to conventional aeration. However, the production of oxygen incurs an additional cost. While the initial investment may be higher, operational costs could be offset by the increased treatment efficiency and potentially lower energy consumption compared to traditional aeration methods.

Currently, there are no available studies focusing on aerobic landfill bioreactors aided specifically by oxygenated leachate recirculation for potential landfill stabilization. Further, there is a lack of extensive comparative studies evaluating the impact of oxygenated leachate recirculation on landfill leachate stabilization and overall municipal solid waste (MSW) landfill management through aerobic techniques. Such studies would provide critical insights into the performance benefits, of using oxygenated recirculation systems in landfill settings. To address this knowledge gap, the study was designed to investigate the effects of oxygenated recirculation on the stabilization of carbonaceous and nitrogenous pollutants in bioreactor landfills. The goal was to offer practical insights and theoretical guidance for accelerating the stabilization of municipal solid waste (MSW).

2 Materials and Methods

2.1 Experimental Setup

The leachate for our experimental work was collected from Saeng-Gok Landfill (Gangseo-gu, Busan, Republic of Korea) operated since April 1996. The composition of the synthetic municipal solid waste (MSW) was adjusted to reflect the typical values for the East Asia and Pacific region (World Bank, 2015) and compacted in each column of the reactor. The organic fraction is composed of food waste (17%) and yard trimmings (19%). The fractional composition of the synthetic MSW is represented in Table 1a. The experiment was performed in three bioreactors composed of acrylic columns of 210 mm diameter and 300 mm high, named R1, R2, and R3, respectively.

Table 1 a) Fractional composition of the synthetic MSW used in the experiment and b) landfill bioreactor operational conditions

a. Waste composition	
Type	Raw waste (%)
Organic waste	36
Paper	26
Soil	5
Wood	5
Plastic	13
Textile	4
Glass and ceramic	5
Metal	
Others	2
b. Operational parameters	
Parameter	Value
Initial temperature (°C)	22
Waste mass (wet basis) (kg)	6.5
Compaction density (kg/m^3)	650
Initial moisture content % (w/w)	50.5
Air flow rate (L/min/kg MSW/day)	0.1
Aeration duration (h/day)	4
Leachate recirculation rate (mL/min)	8.5
Leachate recirculation duration (h/day)	4

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Figure 1 depicts a schematic diagram of the experimental bioreactors. The reactors were sealed with a top cap that included ports for leachate recirculation and aeration. Inside the reactors, the leachate was evenly distributed by a liquid distribution system located at the top. Each reactor column had a leachate collection port at the bottom, and the leachate was collected in a storage tank also situated at the bottom of the reactors. Recirculation of the leachate was achieved using a digital peristaltic pump (Model: EMP 600A, Make: EMS Tech, Korea). A sampling port was provided in the leachate recirculation tube after the peristaltic pump, allowing for leachate sampling. Leachate recirculation is performed through a stainless steel perforated (pore size: 1 mm) rotating distribution manifold (dia: 4 mm) that promotes uniform and consistent distribution of the leachate positioned at the top of the bioreactor lid. The uniform distribution of leachate supports higher and more consistent rates of waste degradation. Efficient distribution ensures that leachate comes into contact with a greater surface area of waste material. This contact is crucial for facilitating microbial activity, which drives the decomposition and stabilization of organic matter in the landfill. Additionally, a temperature sensor is installed at the center of the reactor to periodically monitor the temperature of the waste mass. Two sampling ports, each with a diameter of 4 cm, are located 10 and 20 cm from the top to facilitate periodic sampling of the solid waste. To ensure uniform gas distribution, a layer of small gravel was placed around the aeration pipe, forming a 1 cm gas-conducting gabion. A stainless-steel perforated plate separates the solid waste zone from the leachate collection zone.

2.2 Experimental Design and Operation

Among the bioreactors, R1 and R2 were operated in aerobic mode, and R3 was an anaerobic control. The leachate recirculation was carried out after ten days of filling the bioreactors with synthetic MSW at a compaction density of 650 kg/m^3 and an initial moisture content of 50.5%. The average piece size of the solid waste was approximately 3.0 cm, and they were well mixed before loading to ensure homogeneity of subsequent solid sampling and prevent air paths from the void space (Nag et al., 2018). Intermittent aeration can be an efficient energy-saving approach and an alternative to continuous aeration, significantly reducing power consumption

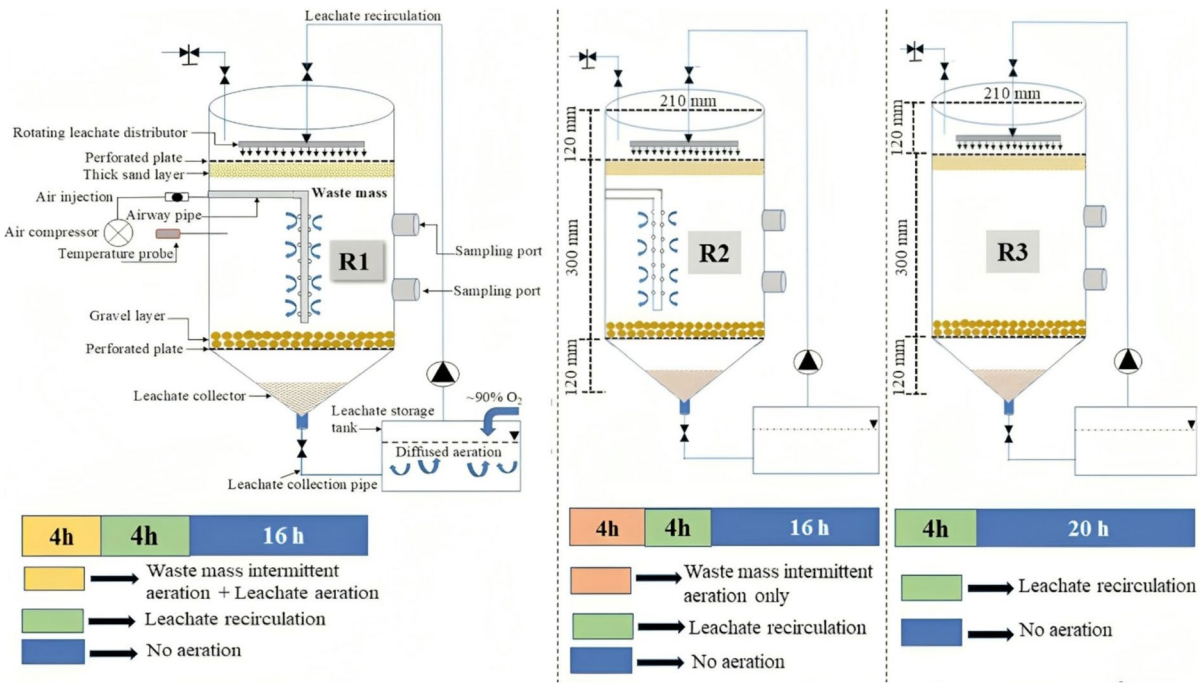


Fig. 1 Schematic representation of the three landfill bioreactors operated under different modes

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costs. By using intermittent aeration, energy costs can be reduced by approximately 75% compared to continuous aeration (Song et al., 2023). The waste mass in aerobic reactors R1 and R2 were aerated in intermittent aeration mode for 4 h/day at an airflow rate of 0.1 L/min/kg MSW/day. In addition, reactor R1 received aeration pretreatment with pure oxygen (~90%) fine bubble aeration (ceramic-type air diffuser, Φ132 × 19H, Daeyang, Korea) at a flow rate of 2.5 L/h for 4 h reaching a dissolved oxygen concentration of 14 mg/L before leachate recirculation.

Fine-pore diffusers are extensively used in wastewater treatment plants due to their superior specific energy consumption and high oxygen transfer efficiencies (OTEs) compared to coarse bubble diffusers (Wang et al., 2020). These diffusers enable the treatment of higher influent loading levels with pure oxygen fine bubble aeration, effectively controlling foam expansion without the need to increase the flow rate (Zhuang et al., 2016). Oxygen transfer improves with increased flow rates, and pure oxygen (PO) transfers more oxygen than air at the same flow rate due to its greater driving force. PO has a dissolved oxygen (DO) saturation concentration up to five times higher than that of air (Rodriguez et al., 2013). Zhuang et al. (2016) observed that increasing the PO flow rate from 0.5 L/h to 1.5 L/h led to a 1.8-fold increase in DO concentration within 300 s. They also noted that there is a threshold beyond which further increases in PO flow rate do not result in higher OTEs, with DO concentration being five times greater at a 2.5 L/h flow rate compared to an equivalent airflow rate. Lee et al. (2013) attributed the difference in oxygen transfer between pure oxygen and air to the fivefold higher DO saturation concentration in pure oxygen. Therefore, a flow rate of 2.5 L/h was selected in our work to maintain sufficient DO concentration during leachate recirculation. Landfill leachates often contain high levels of inorganic and organic contaminants, posing significant environmental risks. One effective on-site treatment method is leachate recirculation, which enhances waste decomposition by allowing the leachate to permeate the solid waste mass (Hussein & Ibrahim, 2023). Leachate recirculation was carried out in all the reactors R1, R2, and R3 at 8.5 ml/min for 4 h/ day. Using leachate recirculation in municipal solid waste landfills, operating as bioreactors, offers substantial environmental and economic benefits. The detailed operational conditions for the bioreactor landfills are summarized in Table 1b.

2.3 Sampling and Analysis

Every 7 days, 40 mL of leachate was sampled from each reactor. After centrifugation, the supernatant was analyzed for pH, conductivity, chemical oxygen demand (COD), ammonia–nitrogen (NH_3-N), nitrate nitrogen (NO_3-N), nitrite nitrogen (NO_2-N), and total phosphorous (TP). The pH, conductivity, ORP, and DO were measured using a YSI professional plus multiparameter meter (Xylem, Japan). The COD was analyzed by the reaction digestion method, and NH_3-N was measured by Nessler method using Humas HS 2300 plus water analyzer (Daejon, Korea). NO_3-N, NO_2-N, and TP were measured by chromatropic acid, ascorbic acid, and gravimetric method, respectively in a Humas HS 2300 plus water analyzer.

10 g of solid samples was extracted from the two sampling ports of the reactors every 15 days and mixed to ensure homogeneity. The solid samples were analyzed for moisture content, and volatile solids (VS). The moisture content was analyzed by oven drying method at 105 °C and the VS measurement was performed following the conventional loss on ignition method at 550 °C.

2.4 Modeling of Organic Substance Degradation

Earlier research demonstrated that the degradation of water pollutants is consistent with the first-order kinetics equation (He et al., 2021). The following microbial-based exponential attenuation model is frequently employed for illustrating the degradation of the organic material (Ma et al., 2021a, 2021b; Zhao et al., 2000):

$$C_x = C_0 \exp^{(-kt)} \quad (1)$$

where C_x is the organic substance concentration in the bioreactors (mg/L) at time t, C_0 is the organic substance concentration at t_0 (mg/L), t is the number of days of the experiment (day), and k is the degradation rate constant (day^{-1}).

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2.5 Microbial Community Structure Analysis

The next-generation sequencing (NGS) based on metagenome amplicon sequencing was used for the determination of bacterial species that formed on the landfill solid waste in the three bioreactors R1, R2, and R3. Approximately 2 g of solid waste samples were collected from each bioreactor at the end of the experiment for microbial community structure analysis, and DNA was extracted. The sequencing primer 16S 27F (5′GAGTTTGATCATGGCTCAG3′), 1492R (5′GGTTACCTTGTTACGACTT3′) were used for bacteria (Hou et al. 2018). The amplified DNA, or amplicons, are then sequenced using high-throughput platforms, producing millions of short DNA reads. A double-stranded DNA template capped by hairpin adapters (i.e., SMRTbell adapters) at both ends, and the library format is created by the DNA Template Prep Kit. Sequencing was performed by Macrogen (Seoul, Korea) using an ABI 3100 automated sequencer with the Big Dye Terminator Kit v. 3.1 (Senthilraj et al. 2016).

3 Results and Discussion

3.1 Dissolved Oxygen and ORP

Dissolved oxygen (DO) is a key ecological parameter for water quality because it is required for the survival of aerobic microbes. Initial analysis of the landfill leachate revealed an anoxic environment with a depleted dissolved oxygen concentration of 0.83 mg/L and a low oxido-reduction potential (ORP) of 12.3 mV. According to Zakaria & Aziz (2018), landfill leachate typically has lower DO levels due to aerobic waste decomposition, where microbes use DO to convert organic materials to inorganic materials. Leachate recirculation and adding pure oxygen (~90%) to the leachate using fine bubble aeration can increase the ORP and help maintain an oxygen-rich environment for the aerobic degradation of the waste matter. An initial drop in ORP values was observed in all bioreactors (R1, R2, and R3), likely due to the high levels of organic matter or other reducing agents in the untreated landfill leachate that consume dissolved oxygen (DO). High DO concentration in the range of 12–16 mg/L was observed throughout the experimental period in the aerobic bioreactor R1 (Fig. 2a). However, the DO concentration in the aerobic bioreactor R2 (without leachate oxygenation) and anaerobic bioreactor R3 were 2–4 mg/L and 0.2–1.4 mg/L, respectively. At the end of the experiment, the ORP value of the stabilized leachate in bioreactor R1 increased to 110 mV which suggest oxidized conditions (Fig. 2b).

The negative ORP values observed initially in anaerobic bioreactor R3 are potentially due to the reducing environment when the DO concentration is < 1 mg/L. The high redox potential associated with aerobic conditions facilitates faster waste stabilization and improved leachate quality. Waste degradation pathways are established in landfills through reduction–oxidation conditions. The oxic condition maintained in the aerobic reactor R1, as indicated by the high DO content and ORP values, promoted aerobic biodegradation of the organic matter present in the bioreactor and accelerated the stabilization of the waste.

3.2 pH and Conductivity

In this investigation, the variations in leachate pH and conductivity were consistently monitored. The results for pH and conductivity of leachate for all three bioreactors are depicted in Fig. 2c. The pH of the leachate in each reactor initially decreased, then gradually increased before stabilizing (Fig. 2c). Because leachate recirculation can increase the hydrolysis of organic matter (Morello et al., 2017; Pohland & Kim, 1999), the pH of all aerobic reactors rapidly decreased and was maintained at around 7.3. The pH levels of the aerobic reactors rose to levels above 8.0 after 60 days of reactor operation. In aerobic landfills, organic acid loss through waste mineralization leads to increased pH levels (Yazici et al., 2017). The comparatively lower pH level in R3 over an extended period indicates that hydrolytic and acidogenic bacteria were predominant and that the accumulation of their degradation products, such as simple soluble organic matter and small molecular organic acids, delayed the methanogenesis phase.

The oxygen levels of the reactors were the primary cause of the pH differences between reactors R1 and R3, and the aerobic reactors did not appear to significantly be influenced by the organic matter content in the system. The pH of the aerobic reactors remained at 8.0–8.3 after day 200, which was consistent with

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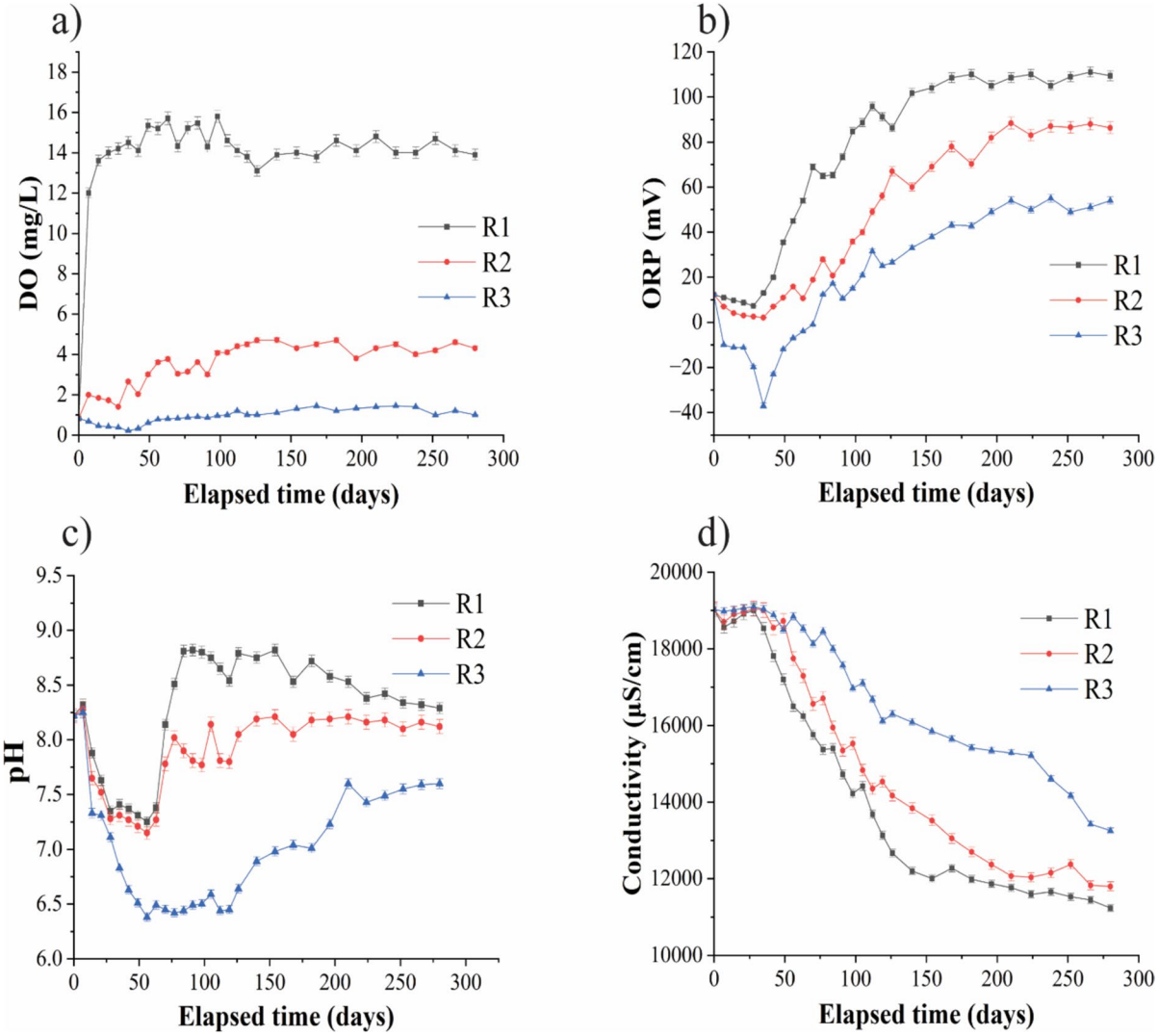


Fig. 2 Variation in recirculated leachate a) dissolved oxygen content, b) ORP, c) pH and d) conductivity with time

prior observations of pH range during stabilization (7.0–9.0) (Liu et al., 2018). At the start of this work, microorganisms rapidly decomposed organic matter, producing low molecular organic acid that accumulated in the leachate for a short time. Due to the sufficient oxygen levels in the simulated aerobic landfill reactors, these small molecular organic acids are rapidly oxidized and broken down into CO_2 and H_2O by microorganisms, preventing the accumulation of organic acids. As a result, the pH of the leachate increased rapidly and remained constant at 8.0 which promotes microbial metabolism (Qiu et al., 2020). The rate of organic matter metabolism is faster, the influence is more apparent before 60 days, and each reactor tends to be stable thereafter.

Electrical conductivity serves as an indicator of ionic strength. Due to the presence of numerous water-soluble ions in the landfill leachate, conductivity values were initially high. During the first fifty days of operation, the bioreactors experienced a brief period of increased conductivity (Fig. 2d). Following this, all reactors exhibited a decline in conductivity measurements. This reduction was attributed to the washout of easily mobilized ions, such as metals, chloride, and sulfate. Additionally, the conversion of sulfate to sulfide and the subsequent precipitation

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of sulfide as heavy metal-sulfides contributed to the decrease in conductivity (Sekman et al., 2011).

3.3 Chemical Oxygen Demand (COD)

COD is a key indicator used to measure the impact of pollutants within landfill bioreactors (Ma et al., 2021a, 2021b) and is commonly employed to evaluate the degradation of municipal solid waste (MSW). The COD levels in all reactors (R1, R2, and R3) initially increased after seven days of operation, followed by a gradual decline over time (Fig. 3a). The increase in hydraulic loading likely provided additional nutrients and moisture, accelerating the rates of hydrolysis and acidogenesis as the leachate was recirculated through the waste (Xu et al., 2014).

Additionally, food waste, which consists of rapidly degrading components, may have led to an abundance of soluble organic matter that the available microorganisms could not fully break down, resulting in higher COD concentrations during the early phase of bioreactor operation (Slezak et al., 2015). Similarly, Luo et al. (2019) observed that, at the start of reactor operation, the dissolution rate of carbonaceous material outpaced the microbial degradation rate due to leachate recirculation and microbial activity (Zhao & Lou, 2017). Consequently, the leachate COD increased sharply. The COD concentrations increased to maximum values of 4720 mg/L, 5500 mg/L, and 5940 mg/L for reactors R1, R2, and R3, respectively, after ten days of reactor operation (Fig. 3a). Nevertheless, the COD concentrations dropped quickly in all three reactors after the microorganisms gradually acclimated to the reactor's conditions after 280 days and their concentration range was 223–1074 mg/L. The above result suggests that the oxygenation of leachate had a significant effect on accelerating the COD degradation rate, reaching the highest value of ~ 85% in reactor R1.

Among the three reactors, reactor R1 exhibited superior COD removal efficiency, likely due to its higher dissolved oxygen (DO) levels, which foster rapid growth of aerobic microbes and enhance the decomposition of organics in the leachate. In contrast, reactor R3, which operates under anaerobic conditions, showed COD concentrations increasing to approximately four times the initial value after seven days. This spike is likely attributable to the difficulty in degrading the complex cellulose structures present in the organic waste under anaerobic conditions. However, once optimal conditions for methanogenic bacteria were established, the COD concentration in R3 began to decline slowly from day 50 onward, reflecting a gradual reduction in organic content. On the other hand, aerobic reactors R1 and R2 demonstrated substantial hydrolysis of complex organics, as evidenced by their lower COD values. Aeration in these reactors increases the oxygen demand for decomposing the chemical compounds in municipal solid waste (MSW), significantly enhancing the biodegradation of organic materials (Eres et al., 2008).

In their findings, Falamaki et al. (2019) observed that aeration of MSW significantly reduced the COD of the generated leachate after 120 days of reactor operation. They concluded that waste aeration can decompose complex organic materials because the injected air provides the necessary oxygen. Cossu et al. (2003) arrived at a similar conclusion in their research. After 120 days of experimentation, the COD level in the anaerobic reactor was 20,000 mg L^{-1}, while the COD levels in the dry and wet aerated reactors were 3,000 mg L^{-1} and 8,000 mg L^{-1}, respectively. Their results demonstrated that aeration positively impacts the rate of waste degradation in landfills. Additionally, the researchers found lower COD levels in their aerated samples compared to their blank sample. Furthermore, Ritzkowski and Stegmann observed a significant decrease in the COD levels of their aerated waste after 20 days, whereas the decrease in COD levels in their anaerobic waste was not as pronounced (Ritzkowski & Stegmann, 2012). As per the regulations for surface water in the World Health Organization (WHO) (Ekute & Etim, 2021) reactor R1 could meet the emission limit of COD (150 mg/L) on day 478, based on the exponential formula (Eq. 1). Meanwhile, the other two reactors could reach the same level considerably later, on days 567 and 742, respectively. In Table 2, we can observe that the oxygenation of leachate significantly accelerated the COD and ammonia nitrogen degradation rate, reaching the highest value (degradation rate, k) in aerobic bioreactor R1. The results indicated that oxygenation and leachate recirculation combined was a useful strategy in expediting landfill stabilization. Earlier studies reported the degradation constant for COD and NH_3-N in the range of 0.015–0.029 day^{-1} and 0003–0.025 day^{-1} respectively (Luo et al., 2019;

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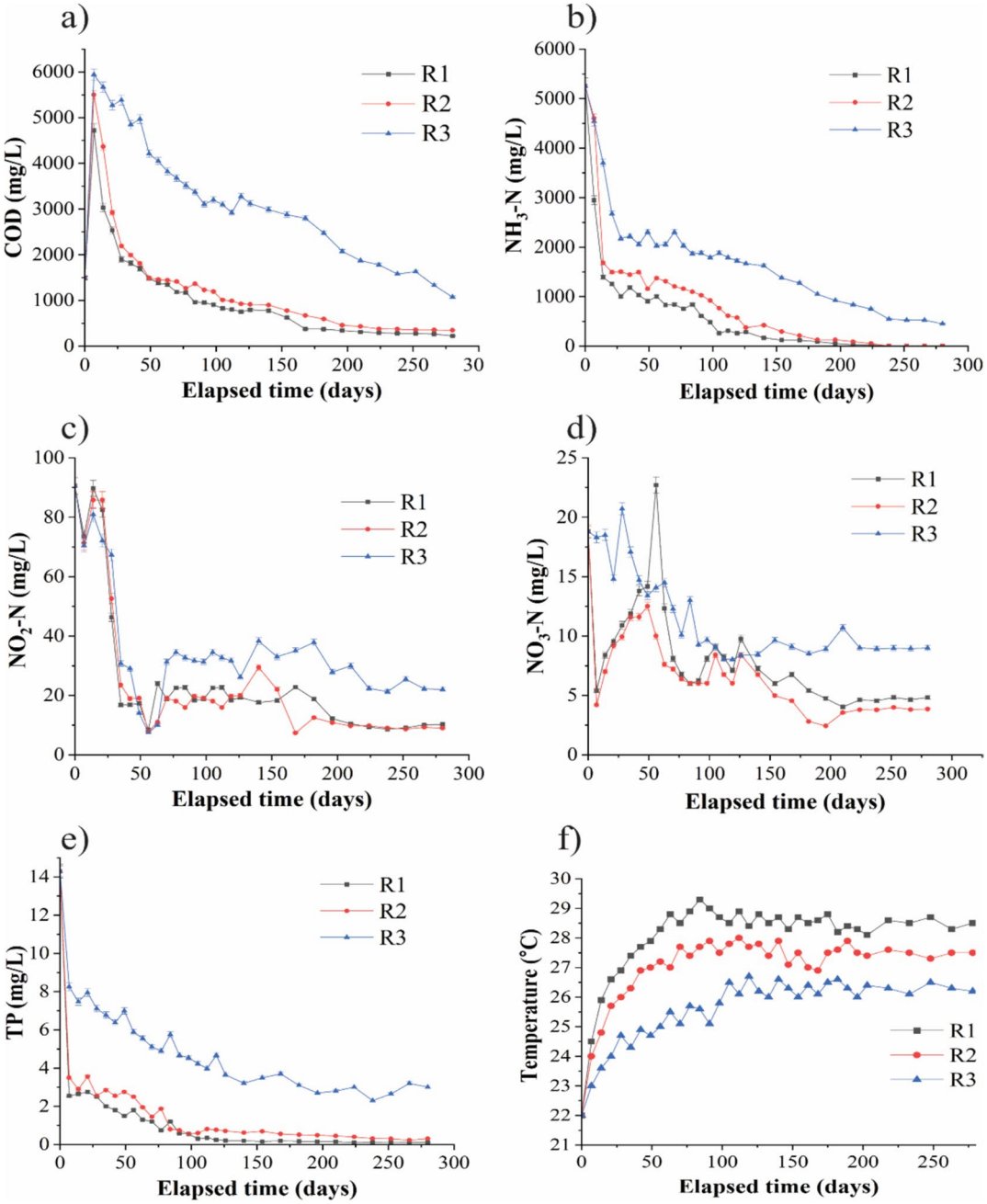


Fig. 3 Recirculated leachate a) COD removal and variation of b) ammonia nitrogen, c) nitrite nitrogen and d) nitrate nitrogen, e) leachate phosphate concentration over time, and f) temperature variation of waste mass over time across three bioreactors operating under different modes

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Table 2 Degradation models of organic substances from aerobic and anaerobic bioreactors

Parameters	Reactors	Fitting formula	t range (days)	Coefficient of determination, R^2	Degradation rate, k (day^{-1})
COD (mg/L)	R1	$y = 1.2525\ e^{-0.01t}$	28–280	0.9695	0.01
	R2	$y = 1.6062\ e^{-0.008t}$	28–280	0.9758	0.008
	R3	$y = 3.6645\ e^{-0.005t}$	49–280	0.9446	0.005
NH_3-N (mg/L)	R1	$y = 0.28061e^{-0.021t}$	35–280	0.9081	0.021
	R2	$y = 0.7317e^{-0.017t}$	35–280	0.8818	0.017
	R3	$y = 0.7028e^{-0.007t}$	35–280	0.9344	0.007
VS (%)	R1	$y = 0.9729e^{-0.003t}$	1–280	0.9604	0.003
	R2	$y = 1.0432e^{-0.002t}$	1–280	0.9834	0.002
	R3	$y = 1.0508e^{-0.002t}$	1–280	0.9684	0.002
Height (cm)	R1	$y = 0.9213e^{-0.004t}$	1–280	0.9833	0.004
	R2	$y = 0.9399e^{-0.003t}$	1–280	0.9870	0.003
	R3	$y = 0.9635e^{-0.003t}$	1–280	0.9858	0.002

Ma et al., 2021a, 2021b). Therefore, our findings align with those reported in other studies.

3.4 Nitrogen Removal

In landfills, ammonia has been identified as a significant long-term pollution problem (Price et al., 2003). During MSW stabilization, most leachate nitrogen is present as ammonia nitrogen and is produced from protein and amino acid degradation. Furthermore, several researchers observed that nitrogen removal was improved during solid waste decomposition in aerated landfills (Berge et al., 2005; Bilgili et al., 2007). Ammonia attenuation is attributed to nitrification and flush-out mechanisms in literature (Cossu et al., 2003). Therefore, it would be advantageous to explore an in-situ nitrogen removal approach using a combination of waste mass aeration and leachate recirculation.

Figure 3b indicated that the ammonia nitrogen decreased steadily in all three reactors. A rapid decrease in the ammonia nitrogen concentration was observed in reactors R1 and R2 because of aerobic nitrification. After 280 days of reactor operation removal efficiency of ammonia nitrogen was achieved at ~ 99% in aerobic reactors R1, R2, and ~ 91% in anaerobic reactor R3 respectively. Because the recirculated leachate contained more dissolved oxygen, reactor R1 demonstrated higher removal efficiency and faster removal of ammonia nitrogen due to rapid nitrification and air stripping because of the high pH value (pH > 8.0). The results indicate that aerobic conditions have a positive impact on nitrogen removal in bioreactor landfills. Additionally, a study (Bilgili et al., 2007) demonstrated that aeration combined with leachate recirculation is a more effective strategy for attenuating ammonia and organic matter. Similar results were observed by Sohoo et al. (2021) where the synergistic operation of leachate recirculation and aeration contributed to the attenuation of ammonia nitrogen, as indicated by the lower ammonia nitrogen levels observed at the end of the experiment.

Figure 3b demonstrated that the NH_3-N removal efficiency of the aerobic reactors was greater than that of the anaerobic reactor. The ammonia nitrogen could be oxidized directly to nitrite nitrogen and nitrate nitrogen due to intermittent waste aeration and leachate recirculation in the aerobic reactors. However, among all reactors, the degradation rate constant (k) was observed to be higher in reactor R1 due to rapid nitrification caused by the oxygenation of the leachate (~ 90% pure oxygen), which augmented its DO content. Because of the high pH conditions, it may be that some amount of NH_4^+-N can be converted to NH_3-N, which was stripped out of the bioreactor R1. Heterotrophic nitrification-aerobic denitrification (HNAD) bacteria exhibit a remarkable tolerance to high organic loads due to their dual functionality in heterotrophic nitrification (HN) and aerobic denitrification (AD) (Deng et al., 2021; Xie et al., 2021). This dual capability allows a single microorganism to perform both nitrification and denitrification processes

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(Ouyang et al., 2020). During this process, HNAD bacteria oxidize ammonium nitrogen (NH_4^+-N) into nitrite (NO_2-N) or nitrate (NO_3-N) using some of the electrons generated from carbon metabolism. The remaining electrons are utilized to reduce the NO_2-N or NO_3-N formed during heterotrophic nitrification into nitrogen gas (N_2) (Bian et al., 2022).

Additionally, research has shown that certain heterotrophic bacteria within the phylum Firmicutes, particularly those of the Bacillus genus, are capable of denitrification, where nitrate serves as the terminal electron acceptor in place of oxygen. It is believed that denitrification occurs in the anoxic zones of aerated reactors, as observed by Berge et al. (2006). The occurrence of simultaneous nitrification and denitrification (SND) in the experimental bioreactors likely contributed to the observed reduction in NO_X (nitrite and nitrate nitrogen) concentrations across all bioreactors (Fig. 3c, d). The presence of Proteobacteria and Firmicutes in the microbial community analysis of the solid samples corroborates their involvement in the heterotrophic nitrification and aerobic denitrification (HNAD) process. These phyla are known to be responsible for facilitating the HNAD process (Li et al., 2024).

3.5 Total Phosphorous (TP)

The majority of the phosphorus in wastewater exists as ortho-phosphates, with a small amount of organic phosphate, mostly found in proteins. The anaerobic microbes have low phosphorous requirements; therefore, the TP concentration in the anaerobic reactor R3 is relatively high compared to the aerobic reactors R1 and R2. In this study, the concentration of TP decreased in all the reactors (Fig. 3e). The leachate TP concentration was measured to be 0.51, 0.78, and 0.99 mg/L for reactors R1, R2, and R3 respectively. In reactor R1, the forced aeration of the leachate with 90% pure oxygen facilitated a better TP removal efficiency. It was observed that during 280 days of reactor operation, the TP concentration was substantially reduced to 0.11 mg/L, 0.31 mg/L in aerobic bioreactors (R1 & R2) and 3 mg/L in the anaerobic bioreactor (R3) from an initial concentration of 14.3 mg/L. However, the TP removal rate during the aerobic process is substantially higher than that during the anaerobic process, which could be attributed to the aerobic conditions in reactors R1 and R2.

4 Solid Waste

4.1 Temperature

The temperature in each reactor ranged from 22 to 29 °C (Fig. 3f), consistent with Zhao et al. (2016), who found that temperatures between 22 and 45 °C facilitate biodegradation and enhance stabilization. The processes of waste mass aeration and oxygenated leachate recirculation contribute to an increase in the temperature of the waste mass as evident from the relatively higher temperatures in bioreactor R1 through the experiment. Aeration introduces oxygen into the waste, stimulating the activity of aerobic microorganisms that break down organic matter. This microbial activity generates metabolic heat, raising the overall temperature. Similarly, oxygenated leachate recirculation ensures a continuous supply of oxygen throughout the waste mass, further enhancing microbial activity and heat production. As a result, these processes create a more favorable environment for accelerated biodegradation and stabilization of the waste.

4.2 Degradation of Volatile Solids

The residue of volatile solids (VS) among the three bioreactors after 280 days is shown in Fig. 4a. Compared to the initial VS content of the synthetic waste, the degradation of organic matter over time in reactors R1, and R2 was approximately 52%, and 45% respectively, all higher than that of reactor R3 (34%). According to Knox et al. (2005), the target value of VS for landfill stabilization is 25%, which reflects that all aerobic bioreactors in our work, especially R1 produced significantly higher stabilization. Reactor R1 demonstrated obvious advantages in waste degradation, potentially due to the additional oxygenation of leachate with ~ 90% pure oxygen and stable moisture content in the waste. Notably, throughout the 280 days of bioreactor operation, the moisture content in all reactors was consistently maintained at approximately 60% due to leachate recirculation.

4.3 Waste Settlement

Municipal solid waste (MSW) settlement is a key indicator for distinguishing between aerobic and anaerobic bioreactor landfills (Eres et al., 2008). The extent of settlement is influenced by several

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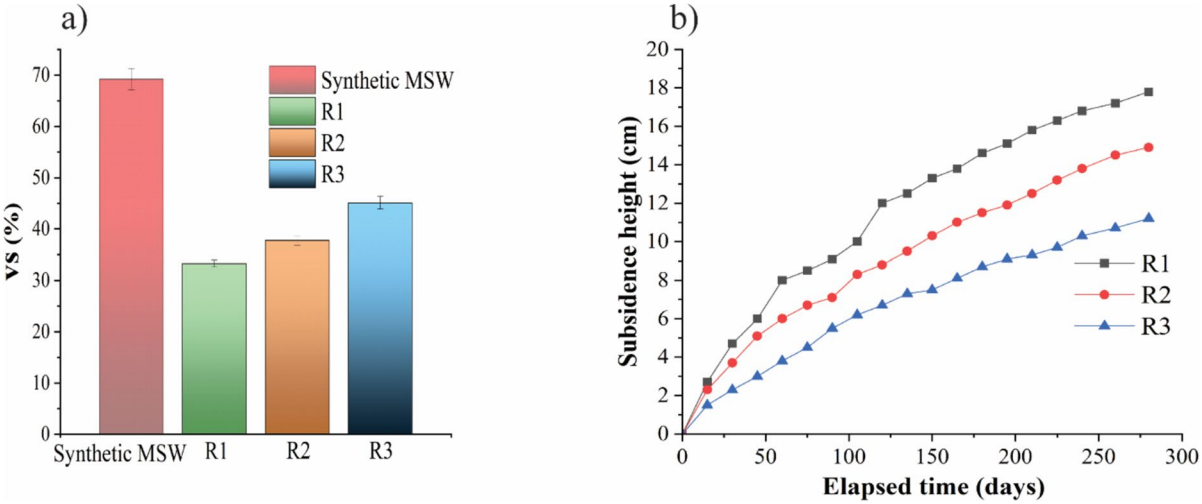


Fig. 4 a) Variation in weight percentage of volatile solids before and after MSW stabilization and b) subsidence height of waste mass with time

factors, including the type of waste, the landfilling technique employed, humidity levels, and the degree of waste compression (Borglin et al., 2004). In our study, we monitored waste settlement over a period of 280 days. The results for both the aerated samples and the anaerobic control are presented in Fig. 4b. As depicted in Fig. 4b, all bioreactors exhibited a rapid initial settlement during the first 21 days, primarily due to gravity-induced settling of the waste. As the experiment progresses, the aerated waste settles more quickly than the anaerobic sample, though the settlement of both samples continues to increase. This is because aeration causes waste to decompose, resulting in a more noticeable settlement in the aerated sample. After 280 days of reactor operation, a higher degree of settlement was achieved in the aerobic reactors R1 and R2 with the setting ratios (cumulative subsidence height/initial height of waste) of ~ 63.5% and ~ 53% respectively while the anaerobic treatment showed ~ 40% suggesting that air enhanced the rate and extent of subsidence under aerobic conditions (Ma et al., 2021a, 2021b).

In their study, Falamaki et al. (2019) measured waste settlement over a 200-day period. As the experiment progressed, the aerated waste settled faster than the blank sample, with both continuing to settle at an increasing rate. The faster settlement in the aerated sample is attributed to aeration, which enhances the decomposition of the waste. In their aerated bioreactor, Giannis et al. (2008) measured a 26% settlement after 510 days. They explained it away as organic materials decomposing naturally. The observed trend also aligns with the findings of other studies. For instance, Erses et al. (2008) found that in their anaerobic bioreactor, settlement occurred after 630 days, with 5% occurring after 374 days for their aerated bioreactor. Ritzkowski et al. (2012) also found that the rate of waste settlement was higher in the vicinity of the aeration equipment installation areas in the landfill, owing to an increase in degradation under aerobic conditions.

Air injection dissipates easily above the landfill, whereas water penetrates in the direction of gravity, reaching the landfill's lowest point and being easily recirculated. Initially, the starting density of the waste is low, and adding leachate can increase the effective stresses, augmenting the waste settlement. Liquid introduction in the form of recirculating oxygenated leachate into the waste can result in additional settling through a number of mechanisms, such as biodegradation, softening of flexible porous materials, lubricating of waste contacts, and increased waste unit weight. The high concentration of oxygen in leachate creates a biofilm around landfill material, activating aerobic microorganisms and reducing organic matter and odour. Pure oxygen contains fivefold more oxygen than air, which helps to activate aerobic microorganisms. The waste matrix assists as a "trickling

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media," allowing for effective leachate recycling and air introduction. The process provides microorganisms with moisture, nutrients, and oxygen to degrade solid and aqueous organic compounds. Settlement was primarily caused by gravity, followed by the emission of pore water and gas. Organics degraded more efficiently in aerobic bioreactor R1 than in R2 due to the higher dissolved oxygen content, which provided a better environment for microbial activity. Oxygen is transferred to the biofilm responsible for degrading organic matter, thereby promoting improved settlement. The increased biodegradation rates can enhance the waste settlement rates in the aerobic bioreactor R1. The schematic representation highlighting the comparative waste settlement in the aerobic bioreactors R1 and R2 is illustrated in Fig. 5. Oxygenated (~90% pure oxygen) leachate demonstrated a greater infiltration effect over typical leachate recirculation and therefore induced a higher settlement of the waste mass.

5 Bacterial Diversity and Community Structure of a Simulated MSW Landfill

5.1 Microbial Community Structure

Using a universal primer pair, a total of 25 phyla were identified across the three bioreactors R1, R2, and R3. The five most abundant phyla consistently found in landfill samples were Bacillota (formerly known as Firmicutes), Bacteroidota, Planctomycetota, and Proteobacteria (Pseudomonadota), which together accounted for over 75% of the total bacterial 16S rRNA gene sequences. Among these, members of the phylum Proteobacteria were the most dominant in all landfill samples, ranging from 34.82% to 26.89%, followed by Bacillota, which ranged from 11.72% to 30.05%, and Bacteroidota, ranging from 7 to 21%, as illustrated in Fig. 6a. The primary functions of Bacillota and Bacteroidetes in landfills involve the decomposition of hydrolytic cellulose and starch polysaccharides (Wang et al., 2017), while Proteobacteria can decompose soluble sugars into monosaccharides and short-chain fatty acids (Kochling et al., 2015; Xu et al., 2016). Fermentimonas, which belongs to the Bacteroidetes phylum, has the capability to hydrolyze and ferment organic matter, playing a crucial role in the degradation of polysaccharides (Wang et al., 2017). Bacillota, observed in high abundance in bioreactor R3, are cellulose-degrading bacteria that are thought to play a crucial role in the anaerobic and methanogenic phases of organic matter decomposition in landfills.

Under aerobic conditions in bioreactor R1, the genus Pseudomonas within the phylum Proteobacteria (as shown in Fig. 6b) plays a key role in breaking down various organic compounds using oxygen, resulting in the production of simpler substances such as carbon dioxide, water, and biomass. This biodegradation process not only reduces the volume of waste but also helps mitigate the release of harmful substances and greenhouse gases. Additionally, the genus Portibacter, an aerobic bacterium

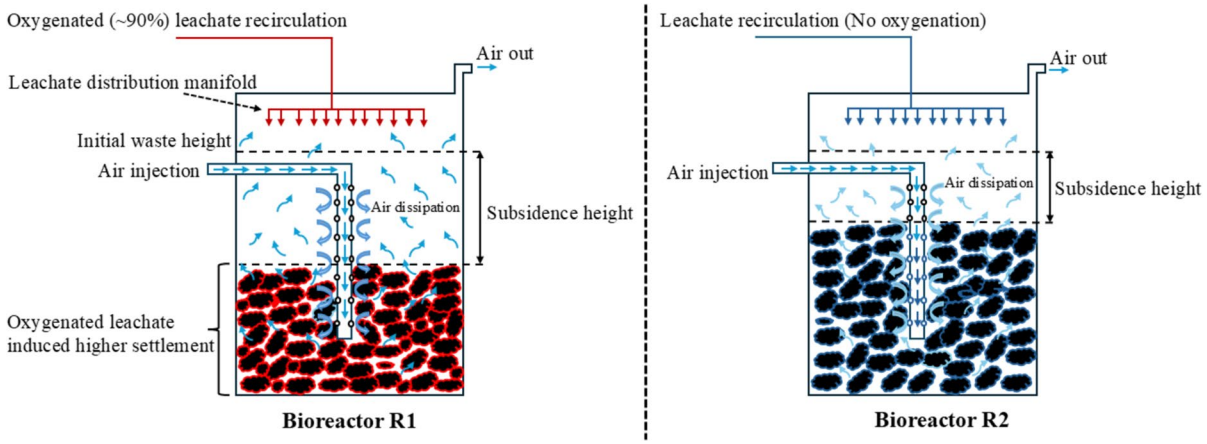


Fig. 5 Schematic representation of the comparative waste settlement in the two aerobic bioreactors R1 and R2

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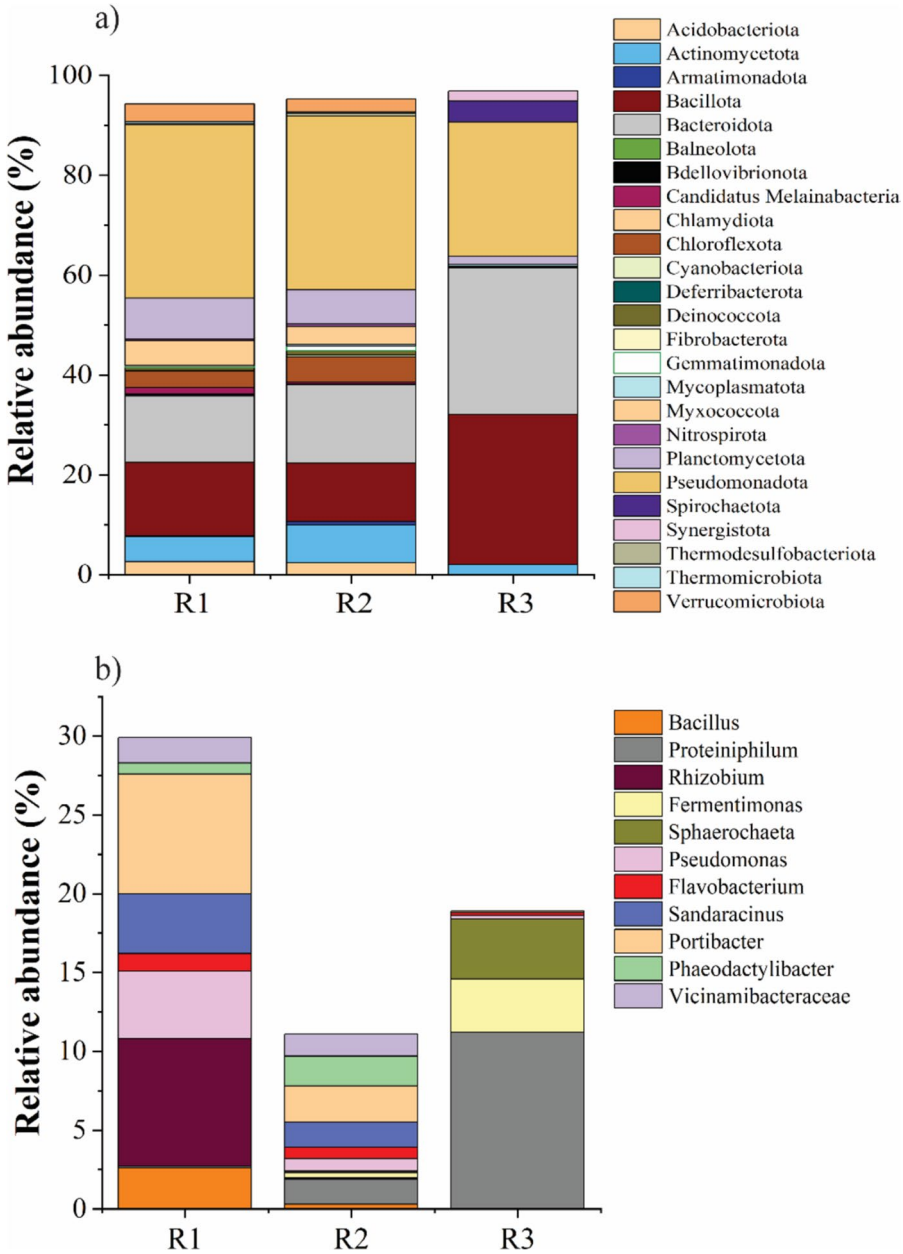


Fig. 6 Relative abundance of the bacterial community at the a) phylum level and b) genus level for the three bioreactor samples based on top ten relative abundance

belonging to the phylum Bacteroidota, is relatively abundant in bioreactor R1 and is capable of degrading a wide range of organic biomacromolecules (Papadatou et al., 2021). Bacillus, a predominant genus within the Firmicutes phylum found in the experimental landfill reactors (Fig. 6b), is primarily involved in carbohydrate fermentation and the degradation of cellulose and polysaccharides (Corbellini et al., 2018). The next most abundant phyla observed were Planctomycetota (ranging from 1.66% to 8.25%), Actinobacteria (Actinomycetota) (2% to 7.5%), Chloroflexota (3.4% to 5%), Myxococcota (3.6% to 4.9%), and Verrucomicrobiota (2.61% to 3.56%) as depicted in Fig. 6a. Other phyla that ranked among the top 10 in abundance across samples included Acidobacteria, Thermomicrobiota, Thermodesulfobacteriota, Nitrospirota, Armatimonadetes, Candidatus Melainabacteria, Gemmatimonadota, Spirochaetota, and Bdellovibrionota. However, their individual contributions were

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relatively minor, ranging from 0.10% to 2.7% of the bacterial sequence set in each sample. Notably, Proteobacteria and Planctomycetota, which were more abundant in bioreactors R1 and R2, are commonly found in aerobic granular sludge and play a role in anaerobic ammonium oxidation (ANAMMOX) metabolism. Acidobacteriota, generally known as aerobic heterotrophs that utilize various carbohydrates, including polysaccharides like chitin or cellulose (Flieder et al., 2021), were observed in bioreactors R1 and R2 but were absent in bioreactor R3.

5.2 Community Richness and Diversity

The indexes of richness and diversity of microbial community were computed, including ASV, Chao1, Good's coverage, Gini-Simpson, and the Shannon index (Table 3). Good's estimator indicated nearly complete coverage. A Good's coverage index value of 1 indicates that the sequencing depth was sufficient to capture the majority of the genetic diversity in the samples. The community richness (Chao 1) showed the highest for R2 and the lowest for R1, which correlates with the number of observed ASVs in the samples. The Shannon and Simpson indices were also derived and had average values of 7.90 and 0.99. The community diversity (Shannon's H index which considers the evenness of ASV distribution) showed the highest microbial richness for R2 and the lowest for R3 (Fig. 7). The index considers both the species richness (the number of species in a habitat) and their relative abundance (evenness). The value of H increases with the diversity of species in a community, as indicated by both the Simpson and Shannon indices. The Gini-Simpson index indicates the likelihood that two randomly selected individuals from a habitat will be from the same species.

Table 3 Coverage estimates for the landfill solid waste bacterial communities

Sample	ASVs	Chao1	Shanon (H)	Gini-Simpson	Good's coverage
R1	415.0	415.0	7.801	0.989	1.0
R2	589.0	589.0	8.341	0.993	1.0
R3	423.0	423.0	7.625	0.987	1.0

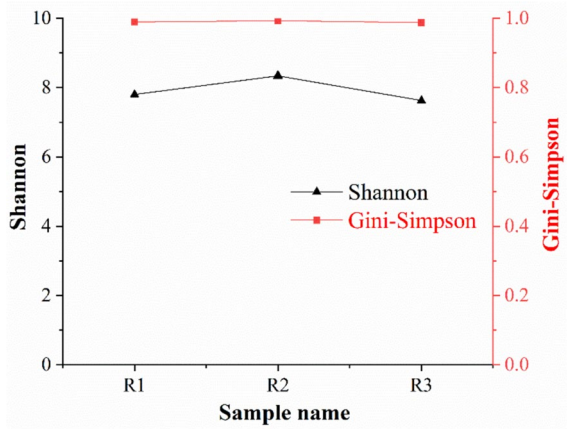


Fig. 7 Microbial community diversity index of tested solid waste samples from the bioreactors

6 Conclusions

The aerobic landfill bioreactor studied here provides a sustainable waste management solution primarily through faster waste stabilization. Employing leachate recirculation not only enhances moisture control but also accelerates organic decomposition and promotes leachate purification via microbial activity. This approach can yield significant cost savings in leachate treatment, particularly beneficial in locations with limited leachate management options. Among the three landfill bioreactors studied (R1, R2, and R3), R1 exhibited the highest settlement sequence, indicating superior waste stabilization. It achieved approximately 63.5% air space recovery, facilitating potential reuse. Leachate recirculation in R1 led to a significant reduction in organic concentration, with COD levels decreasing by up to 85%, and NH_3-N concentrations in treated leachate dropping below 2 mg/L using aerobic processes. R1 also showed the most substantial decrease in organic and nitrogenous pollutants in MSW leachate, suggesting lower pollution risks and effective decontamination. Overall, the use of leachate recirculation with 90% pure oxygen in R1 proved promising for enhancing leachate decontamination and accelerating MSW stabilization in aerobic bioreactor landfills, supporting improved landfill management strategies. This result offers experimental support for better landfill management strategies aimed at accelerating MSW stabilization in aerobic bioreactor landfills.

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Anticipated outcomes from this research include environmental benefits such as enhanced landfill capacity and reduced groundwater contamination risks through oxygenated leachate recirculation. This approach also promises economic savings by extending landfill lifespan and reducing operational costs. Additionally, proactive odor mitigation could improve community relations by transforming perceptions of landfill facilities. Overall, the aerobic landfill bioreactor with oxygenated leachate recirculation represents a significant step towards sustainable, low-carbon, and zero-discharge landfill operations.

Acknowledgements The authors are thankful to MS student Ms. Shazia Noorin for her assistance in experimental analysis.

Author Contributions Conceptualization: [Arnab Ghosh]; Methodology: [Arnab Ghosh]; Formal analysis and investigation: [Arnab Ghosh]; Writing—original draft preparation: [Arnab Ghosh]; Writing—review and editing: [Sung Hyuk Park]; Funding acquisition: [Sung Hyuk Park], [Jurng-Jae Yee]; Resources: [Sung Hyuk Park], [Jurng-Jae Yee]; Supervision: [Sung Hyuk Park].

All authors read and approved the final manuscript.

Funding This work was supported by a National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (2021R1I1A3060770) and the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (2016R1A6A1A03012812).

Data Availability The data that support the findings of this study are available on request from the corresponding author.

Declarations

Ethical Approval Not applicable.

Consent to Participate Not applicable.

Consent to Publish Not applicable.

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

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