JEE Journal of Ecological Engineering

Journal of Ecological Engineering, 2025, 26(12), 341–357
https://doi.org/10.12911/22998993/208867
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Received: 2025.06.22
Accepted: 2025.09.01
Published: 2025.10.01

Leachate recirculation in a laboratory-tested bioreactor landfill: Effects of biodegradation

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ABSTRACT

The amount of waste generated in Bandung City taken to the Sarimukti TPA (final processing site) exceeds 30% of the total generation. This is not by Presidential Decree no. 97/2017, which places landfills at the bottom of the hierarchy because waste decomposition takes 30–50 years and can potentially become an environmental problem in leachate pollution, landfill gas emissions, and disease vectors. The landfill bioreactor innovation is a reactor with a microbiological process that can accelerate the decomposition and stabilization of waste. The landfill bioreactor was operated anaerobically for 138 days. Waste in the landfill bioreactor produces leachate, which is used for recirculation. Leachate recirculation improves physical, chemical, and biological conditions, thereby stabilizing biodegradation and waste. The biodegradation rate is reviewed based on leachate, gas, and settlement parameters. Leachate recirculation variations are 0%, 6%, and 12% of the reactor volume. Leachate recirculation of 12% (120 L/day) is thought to be able to increase the degradation rate, indicated by a more significant COD removal efficiency, 85.82%, compared to recirculation of 6% (60 L/day), 77.87%. This is also supported by the measured settlement rate (decrease in the waste surface), recirculation 12%, 16.61%, compared to recirculation 6%, 9.13%, and without recirculation, 4.02%. However, methane gas (CH_4) production in recirculation 6% has an average of 0.034 L/day higher than recirculation 12%, which is 0.027 L/day. This is thought to be due to the presence of an inhibitor in the form of $O_{2,}$ due to the higher injection volume of the leachate recirculation process at recirculation 12%. Apart from that, it is also suspected that gas is difficult to release into the atmosphere because the waste condition is increasingly saturated, which is indicated by vertical permeability. Apart from that, the waste condition is starting to become saturated, compressing the pore space, making it difficult for gas to be released. The MANOVA test with Minitab was used to identify the effect of leachate recirculation on biodegradation rates (COD and methane parameters) and settlement. The results show an influence of the leachate recirculation volume on the rate of biodegradation (methane and COD gas parameters) and settlement.

Keywords: bioreactor, landfill, degradation, leachate, recirculation, settlement.

INTRODUCTION

Solid waste management in Bandung City remains a challenge for the local authorities. In 2020, the amount of solid waste generated in Bandung City delivered to the TPA Sarimukti (solid waste processing site) exceeded 30% of the total generation, or 2200 tons/day [Surya, 2020]. This contradicts Presidential Regulation Indonesia Number 97 of 2017 on National Policy and Strategy, which places landfills at the bottom of the hierarchy. Landfills are at the bottom of the hierarchy because solid waste degradation in landfills takes 30 to 50 years and can potentially become an environmental hazard in leachate contamination, landfill gas emissions, and disease vectors [Sanphoti et al., 2006]. The bioreactor landfill innovation is a reactor with a microbiological process that may enhance the decomposition of organic waste, the conversion rate of complex organic compounds, the effectiveness of methods that do not occur in conventional landfills, and prevent the potential negative impact of landfills on living creatures and the environment [Warith, 2002]. Bioreactor landfill can accelerate solid waste degradation with better leachate recirculation [Rodrigo-Ilarri et al., 2020].

Leachate recharge has environmental benefits and is able to solve leachate treatment problems [Zhang et al., 2022]. Leachate tends to be gathered in conventional landfills; however, with this method, it will be recirculated back into the waste matrix to enhance physical/chemical/biological conditions, thereby accelerating biodegradation, and shortening up waste stabilization time. According to Damanhuri [2012], the key factor to determine the stability of a landfill is the leachate concentration that fulfills applicable quality criteria; biogas potential is negligible; and settlement decrease is negligible. Leachate recirculation can reduce the organic load in leachate by up to 90%, which is quantified as a COD (chemical oxygen demand) an indicator. Organic load decreased since it has been transformed into biogas, specifically methane gas (CH_4) and carbon dioxide (CO_2) [Damanhuri, 2012]. Methane gas will be caught and recovered under regulated conditions, increasing the economic value and utility of gas recovery.

This research study uses a laboratory-scale bioreactor landfill by recirculating the leachate produced into the waste matrix with variations in discharge. It is hoped that by applying the landfill bioreactor innovation on a field and pilot scale, it will be possible to accelerate the rate of waste stabilization and enhance biodegradation, which will increase the environment's carrying capacity. This is particularly necessary in Indonesia, where landfill operations typically involve open dumping. Leachate effluent, biogas, and settlement quality parameters are frequently measured to observe the biodegradation rate.

MATERIALS AND METHODS

The steps of this research are illustrated in the following research flowchart (Figure 1).

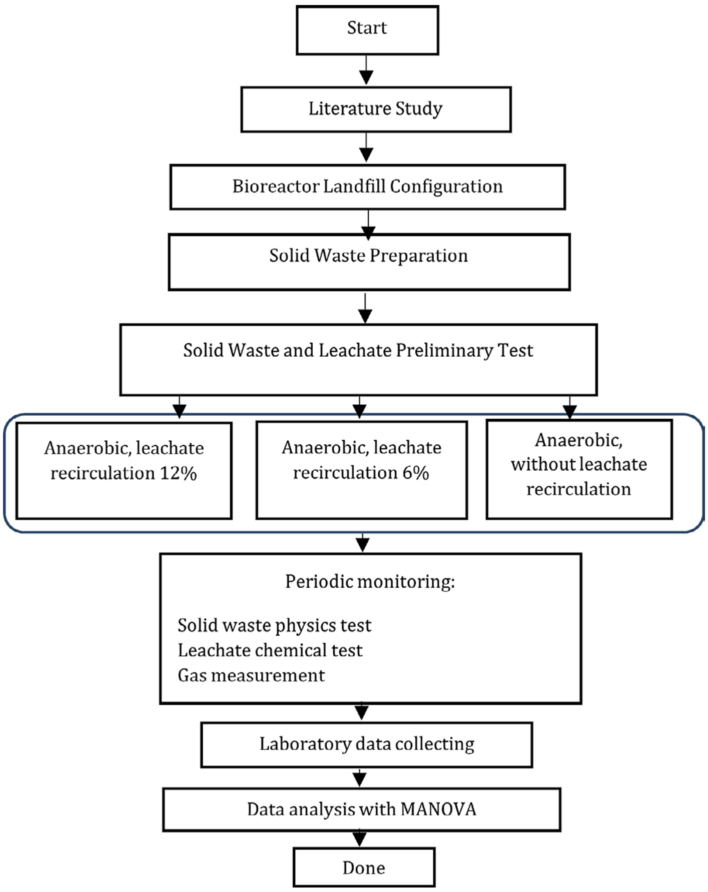

Figure 1. Research flowchart

Furthermore, the explanation of each step is presented as follows:

1. Literature study of theories related to the solid waste degradation process through different books and scientific journals.
2. Bioreactor landfill configuration – configuring the bioreactor landfill compartment system for best performance. The bioreactor landfill is made of permanent concrete construction with a cover made of PVC glued with sealant to make it air and watertight. The volume of the landfill bioreactor is 1,0048 m^3.
3. Solid waste preparation – the solid waste applied in this research must be homogeneous regarding generation, composition, size, density, and field capacity.
4. Solid waste preliminary test – since it is important to ensure that the solid waste maintenance process in the bioreactor landfill runs as smoothly as possible, an initial preliminary test of the solid waste's properties is conducted to gather information about the materials. The initial tests were conducted for solid waste permeability, ultimate analysis, proximal analysis, and leachate chemical analysis
5. Bioreactor landfill operation – there are 3 bioreactors landfill used in this study, including:
   - leachate recirculation 12% of waste generation (120 L/day), daily recirculation, anaerobic operating mode;
   - leachate recirculation volume is 6% of waste generation (60 L/day), daily recirculation, anaerobic operating mode;
   - without leachate recirculation, anaerobic operating mode.
6. Periodic monitoring of bioreactor landfills relying on parameters for the solid waste physics test, leachate chemical test, gas measurement, and settlement measurement is necessary to observe the degradation process.
7. Laboratory data collection – regularly monitor the bioreactor landfill using the leachate chemical test, the solid waste physics test, the gas measurement, and the settlement measurement parameters, which are gathered as laboratory data.
8. Data analysis with MANOVA – all laboratory data collected were then analyzed using one-way MANOVA to see the effect of leachate recirculation on the biodegradation and waste settlement rate.

Bioreactor landfill configuration

The bioreactor landfill compartment and configuration of this research are illustrated in Figure 2.

Solid waste preparation

Three bioreactor columns were evenly divided to hold the 1.1-ton waste from PPS Sabuga ITB used in this study. The composition of the waste used for this study is shown in Table 2, referring to the 2019 dry season waste composition at the TPA Sarimukti. Since minerals and hazardous solid waste might inhibit the growth and activity of microorganisms in the bioreactor, they were excluded from the study. The composition and weight of waste samples refer to the dry season sampling results of TPA Sarimukti, which can be seen in Table 1. The solid waste from PPS Sabuga ITB was then chopped into pieces between 100 and 150 mm in size after the plan of the study had modified its composition. This was done because the waste could produce 16 times more methane than waste chopped into pieces smaller than 15 mm [Buivid et al., 1981]. The production may tend to be acidic and interfere with the creation of methane gas if

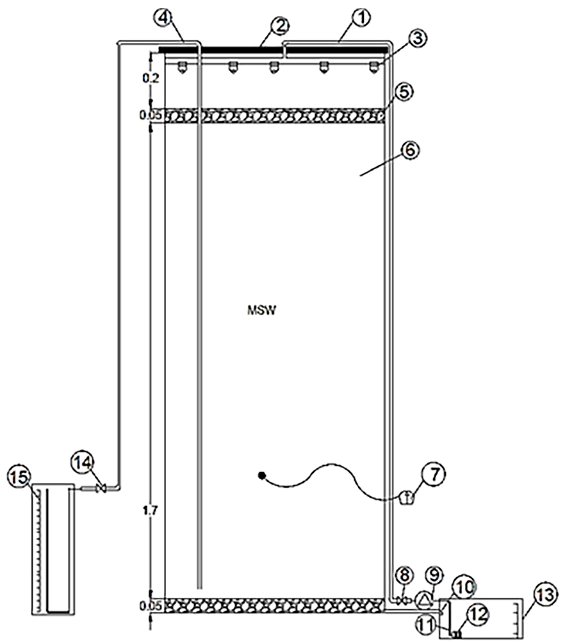

Figure 2. Bioreactor landfill configuration. 1 – leachate recirculation pipe, 2 – reactor lid, 3 – spray nozzle, 4 – gas hose, 5 – gravel , 6 : MSW matrix, 7 – port thermometer and thermocouple, 8 – valve leachate recirculation pipe, 9 – leachate recirculation pump, 10 – outlet leachate, 11 – leachate recirculation hose, 12 – filter , 13 – leachate tank, 14 – valve pipe gas, 15 – hose

Table 1. The composition and weight of waste samples refers to the dry season sampling results of TPA Sarimukti

Solid waste composition	Percentage (%)	Weight (kg)
Food waste	46.27	167.46
Garden waste	6.44	23.31
Plastic bottle	0.76	2.75
Plastic glass	1.05	3.80
Plastic container	3.17	11.47
Plastic wrap	11.31	40.93
Plastic bags	9.05	32.75
Papers	10.42	37.71
Metals	0.23	0.83
Glass	0.88	3.18
Textile	3.8	13.75
Rubber	0.55	1.99
Diapers	5.33	19.29
Others	0.74	2.68
Total	100	361.91

Note: Nippon Koei Co., Ltd, 2019.

the solid waste size is too tiny, as this can lead to random solid waste hydrolysis [Jin, 2005]. The garbage is diced, combined, and then compacted to a density of 400 kg/m^3 in a bioreactor. This density aligns with the literature, which states that full-scale landfill compaction should be between 400 and 750 kg/m^3 [Tchobanoglous et al., 1993]. According to Caicedo et al. [2017], compaction is necessary to influence the environmental factors in solid waste piles that affect landfill stabilization, such as leachate permeability and the growth and metabolism of microorganisms. Compaction is carried out by inputting solid waste with a weight according to the volume of the bioreactor landfill and then compacting it manually. Once the solid waste has been compressed, one kilogram is needed for laboratory test samples. After that, the landfill bioreactor is sealed tightly, with a field capacity between 60 and 70% to keep the waste matrix's humidity levels stable [Jin, 2005]. The leachate pipe outputs will have valves installed as part of the field capacity maintenance efforts.

Determining variation of leachate recirculation

The following formula was used to calculate variations in leachate recirculation in this research [Reinhart et al., 2002]:

$$R_L = \frac{V_1}{V_S \cdot t} \cdot 100\% \qquad (1)$$

where: V_1 – volume of leachate injected, V_s – volume of bioreactor landfill, t – recirculation time.

Several field studies have stated that the volume of recirculated leachate injection positively impacts methane gas production (one of the waste stability parameters), as shown in Table 2. Meanwhile, Jin [2005] uses a leachate recirculation discharge of 12% of the reactor volume with a daily recirculation frequency. However, Ahmadifar et al., (2016) achieved 50–60% methane generation using a leachate recirculation discharge of 11% of the reactor volume. Excessive recirculation volumes can deplete buffer capacity and stop methanogenic activity [Jin, 2005]. The leachate injection volume in some study cases can be seen in Table 2.

Table 2. Leachate injection volume in multiple study cases

Ref	Area (m^2)	Operation time (year)	Injection volume (m^3)	*Loading* (month^{-1})	Methane generation
V´elez (1999)	230	0.15	12.8	1.6%	50%[2]
Mehta et al. (2001)	930	3	3000	1.3%	220%[2]
Morrisa et al. (2003)	4000	6	1920	0.16%	700%[2]
Ozkaya et al. (2004)	15000	0.2	3000	0.25%	10%[1]
	36000	8	3020 /year	-	
	97000	2	742 /year	-	
Benson et al. (2007)	121000	1	19771 /year	-	14–69%
	56000	4	1419 /year	-	
	178000	4	17035 /year	-	
Manzur et al. (2012)	3000	0.5	116	0.1%	15%[1]; 150%[2]
Chung et al. (2015)	2000	0.69	-	-	230%

Note: [1] Methane concentration, [2] methane generation [Liu et al., 2018].

Solid waste parameters

Solid waste permeability tests, temperature, proximal, ultimate, and other physical and chemical waste parameters are analyzed. The ASTM D 2216–92 and ASTM E 897–88 guidelines use gravimetric principles to guide the approximate test for moisture and volatile solid waste content. The amount of solid waste in water and organic matter can influence potential leachate production volume and quality. Solid waste degradation rate is significantly influenced by moisture content. This is due to the function of the moisture content in solid waste as a medium for spreading organic material for microorganisms [Warith et al., 2005]. Microorganisms, particularly methanogenic bacteria, need between 50 and 60 percent humidity to decompose solid waste properly. Solid waste stabilization can also be achieved by limiting the movement of water vapor in addition to the moisture content. According to Jin, (2005), monitoring humidity in landfill operations, including moisture content and water vapor movement, is fundamental.

The volatile solid value is an important part of landfill bioreactors' anaerobic waste degradation process. A high volatile solid value suggests that solid waste can be transformed into other materials, like heat, compost, fresh cells of microorganisms, and gases like CO_2, CH_4, NH_3 and SO_2 [Tchobanoglous et al., 1993]. The rate of leachate and movement of gases that supports the overall performance of landfills is determined in part by waste permeability. The ASTM D2434 waste permeability test adopts the constant head principle. A thermometer is used daily to measure the temperature and monitor the degradation phase. The initial temperature in a landfill bioreactor is generally between 28–30 °C [Budihardjo et al., 2019]. Then, due to bacterial activity, the temperature will rise and fall during hydrolysis, the first step of anaerobic waste degradation that converts complex molecules into simpler ones [Oktiawan et al., 2019].

The temperature will rise until it reaches the thermophilic phase between 45 and 60 °C. This phase is where bacterial metabolic activity peaks and biodegradation happens more rapidly [Kumar et al., 2011]. High temperatures are a sign that the substrate is available for fermentation, which provides energy for the growth of microorganisms. The bacteria that play a role in influencing waste temperature are mesophilic and thermophilic. Nitrogen and ammonia are formed in part by thermophilic bacteria. The temperature will progressively drop after entering the thermophilic phase until it reaches 28 to 30 °C, which shows that mesophilic bacteria are starting to replace thermophilic bacteria in terms of activity. Mesophilic environments are optimal for waste stability during the breakdown process [Oktiawan et al., 2019].

Leachate parameters

Analyzing the parameters pH, temperature, TSS, TDS, COD, BOD_5, NH_4^+ – N, Fe, and Zn of leachate generation can be used for monitoring the ongoing degrading process of solid waste. During the investigation, a 500 mL leachate sample from the bioreactor landfill was taken and will be examined once a week based on the anaerobic bioreactor's landfill waste degradation phase. Table 3 displays the leachate quality test standards, shown below.

Leachate pH monitoring is an essential parameter to determine the anaerobic waste degradation stage in a landfill bioreactor. The process of anaerobic waste degradation begins with a decrease in the oxygen supply available in the pores of the waste. When oxygen is depleted, the anaerobic

Table 3. Leachate quality test standards

Parameter	Method	Test Standards
pH	pH meter	SNI 6989.11:2019
Temperature	Thermometer	SNI 6989.23-2005
TSS	TSS meter	SNI 6989.3:2019
TDS	TSS meter	SNI 6989.27:2019
COD	Closed Reflux	SNI 6989.73:2019
BOD_5	*Bioassay*	SNI 6989.72:2009
$NH4^+$ – N	Distillation, acid – base titration	SNI 19-6964.3-2003
Fe	AAS	SNI 6989.4:2009
Zn	AAS	SNI 6989.7-2009

phase begins, and other substances such as nitrates, sulfates, oxidized manganese compounds, and iron compounds act as oxidants. The pH is typically 6.7 during this transitional phase [Vesilind et al., 2002]. Then the anaerobic phase in the landfill bioreactor is characterized by rapid hydrolysis of polymer compounds and a decrease in redox potential (reduction-oxidation). Complex organic compounds, like alcohol, carboxylic acids, and carbon dioxide, are hydrolyzed into smaller molecules during the anaerobic acid phase. When organic acids form, pH falls [Farquhar and Rovers, 1973]. In the acidification process, the pH range is typically between 4.7 and 7.7 [Vesilind et al., 2002]. Methane-producing bacteria use breakdown products as substrates during the methane production phase to produce a gas mainly composed of carbon dioxide and methane. Because the bicarbonate system buffers organic acids, when they break down, the pH rises to nearly neutral levels [Bozkurt et al., 2000]. According to Vesilind et al., (2002) the leachate pH is 7.1–8.8 during the maturase phase and typically displays 6.3–8.8 during the methanogenesis phase. pH conditions are also closely related to heavy metals (Fe and Zn). Heavy metals (Zn and Fe) in well-buffered solid waste deposits are typically kept in high pH environments, and their concentration in the leachate is usually low. Meanwhile, solid waste loses its ability to immobilize heavy metals when pH drops. Heavy metals become mobilized in landfill bioreactors due to acidification.

Two basic criteria, BOD and COD, can be used to quantify the various organic compounds present in leachate. According to the researchers, the BOD/COD ratio indicates the material's degree of biodegradability, or more specifically, the processability of the organic material present in the leachate. The BOD/COD ratio is usually less than or equal to 1.0. However, the BOD/COD ratio is typically higher than 0.5 when working with materials that are challenging to treat, such as leachate. Young landfills have leachate samples with high BOD and COD values of 60,000 mg/L and 130,000 mg/L [El-Fadel et al., 2003]. The majority of nitrogen in the leachate is made up of ammonium. As a result of amino acids and other organic nitrogen compounds decomposing biologically, leachate contains ammonia nitrogen, or NH_4^+–N. Total Kjeldahl nitrogen (TKN) is the sum of organic and ammonia nitrogen. The release of dissolved nitrogen into leachate from waste happens over an extended period, in contrast to that of dissolved organics [Umar et al., 2010]. Because the nitrogen portion of the biodegradable waste substrate is hydrolyzed and fermented, the ammonia nitrogen concentrations rise as the landfill ages. Because of its persistence in anaerobic environments, ammonia is regarded as a significant long-term contaminant.

Table 4. Composition of gas produced by landfill

Gas	Composition (%)
Methane (CH_4)	45–60
Carbon dioxide (CO_2)	40–60
Nitrogen (N2)	2–5
Oxygen (O_2)	0.1–1
Ammonia (NH_3)	0.1–1
Hydrogen sulfide (H_2S)	0–1
Hydrogen (H_2)	0–0.2
Carbon monoxide (CO)	0–0.2
Gas lain	0.01–0.6

Note: Tchobanoglous, 1993; EPA, 1995.

Gas parameters

The anaerobic waste degradation process in landfills produces gases including ammonia (NH_3), carbon dioxide (CO_2), carbon monoxide (CO), hydrogen (H_2), hydrogen sulfide (H_2S), methane (CH_4), nitrogen (N_2), and oxygen (O_2). Table 4 displays the composition of the gas produced by the landfill, which can be seen below.

During the first phase of waste decomposition, aerobic bacteria consume oxygen (O_2) and break down long molecular chains of complex carbohydrates, proteins, and lipids in the organic waste components. Stage II decomposition begins after the landfill's oxygen (O_2) supply runs out. During anaerobic process, bacteria transform substances into acetic, lactic, and formic acids and alcohols like methanol and ethanol [EPA, 1995]. Numerous anaerobic bacterial species break down the organic acids generated in phase II to produce acetate, an organic acid, which triggers phase III breakdown. Methane-producing bacteria start growing in the landfill because of this process, making the environment more neutral. It is symbiotic, or mutually beneficial, between acids and methane-producing bacteria (CH_4). Compounds consumed by methanogenic bacteria are produced by bacteria that produce acid. Acid-producing bacteria will be poisoned by methanogenic bacteria when they eat too much acetate and carbon dioxide (CO_2)

[EPA, 1995]. When landfill gas's composition and generation rate remain roughly constant, Phase IV decomposition starts. Phase IV landfill gas typically comprises 45–60% CH_4, 40–60% CO_2, and 2–9% additional gases, like H_2S, by volume. Phase IV produces gas steadily for 20 years or longer, but after the solid waste is disposed of in a landfill, gas will continue to be released for at least 50 years [Crawford and Smith, 1985]. Using a gas analyzer, this study examines gas to identify key gas properties such as CH_4, CO_2, O_2, and CO. Daily measurements are made to monitor the degradation phase.

Settlement

Settlement can be interpreted as a decrease in landfill land due to the loads acting on it or due to the effects of decomposition of waste material. The load can be from structures built on landfill land or the waste pile. Settlements in solid waste include intermediate, primary, and secondary settlements. This study focuses on secondary settlement, bio compression, which is long-term compaction impacted by waste material reformation and organic material decomposition [Sowers, 1985]. A laser distance meter measures the drop in waste surface three times a week, indicating settlement over time. According to Damanhuri (2012), negligible settling indicates that solid waste in landfills stabilizes.

RESULTS AND DISCUSSION

Initial characteristics of solid waste

The solid waste weighs ± 1.1 tons and originates from PPS Sabuga ITB. Solid waste has a consistent density of 400 kg/m^3 and a size range of 100 to 150 mm. The first waste permeability test results showed that waste compacted at 400 kg/m^3 with a 12% leachate recirculation variation was 4.509 cm/hour (medium rate); at 6% leachate recirculation, the variation is 0.381 cm/hour (slow rate); and at 2.961 cm/hour (medium rate) without leachate recirculation. The permeability test results show the speed at which liquids and gases travel through the waste matrix. Table 5 displays the liquid and gas flow movement classification according to the permeability coefficient value.

Table 5. Classification of liquid and gas flow movement according to the permeability coefficient value

Class	Permeability (cm/hour)
Very slow	< 0.125
Slow	0.125–0.50
Quite slow	0.50–2.00
Medium	2.00–6.25
Quite fast	6.25–12.5
Fast	12.5–25.00
Very fast	> 25.00

Note: Uhland dan O'neil dalam LPT [1979].

There are differences in the permeability values among the three landfill bioreactors, although they have the same percentage of solid waste. Estimates indicate that the type of waste intake varies somewhat, even though the percentage and composition are often the same. In landfill bioreactors, for instance, different forms of food waste must be fed; for instance, the required composition of food waste is 46.27%. There may be a difference in permeability values depending on the type of reactor used. For instance, a landfill bioreactor with 12% leachate recirculation may receive a higher rice input; a reactor with 6% leachate recirculation may receive fruit; and a reactor without recirculating leachate may receive meat. The initial pace at which leachate forms in the holding tank is affected by this permeability. After 30 days of waste loading, leachate generation occurs in reactors that will recirculate 12% of the leachate, and then reactors that do not. On the other hand, leachate generation takes 40 days from the time the trash is loaded into the reactor, which would recirculate 6% of the leachate. Figure 3 shows the leachate production within 30 days.

The solid waste field capacity preliminary test findings showed that variations of 12% leachate recirculation were 38%; variations of 6% leachate recirculation were 41%; and variations without leachate recirculation were 40%. A 6% leachate recirculation variation has a permeability coefficient in the slow class. In contrast, a 12% leachate recirculation variation has a medium class permeability coefficient, resulting in a lower field capacity value. As a result, a 12% leachate recirculation variation can pass leachate more quickly than a 6% variation. According to Jin, (2005) research, the landfill bioreactor's field capacity was between 60 and 70 percent to maintain the solid waste matrix's humidity. The leachate pipe outputs will have valves installed as part of the field capacity maintenance efforts.

The moisture content test findings for waste samples with a 12% leachate recirculation

Figure 3. Leachate production within 30 days

variation were 56.12%; the variance with a 6% leachate recirculation variation is 52.18%; and the variation without a leachate recirculation variation is 54.90%. Overnight humidity can be reached by recirculating leachate into the waste matrix and preserving its field capacity. The water content test results for waste samples with a leachate recirculation variation of 12% were 82.75%; the variation with 6% leachate recirculation is 83.25%; and in the variation without leachate recirculation, it is 77.5%. This volatile content value will decrease as the activity of microorganisms increases. Organic materials will be degraded and shaped by the activity of microorganisms at the acidification and methanogenesis stages into other N forms [Tchobanoglous et al., 1993]. Based on these results, the potential level of biodegradability of organic materials contained in the waste is indicated. The elements C, H, O, and N, respectively, are uniformly distributed throughout the solid waste sample used in this research study. The percentages of each element are 41.712%, 5.737%, 25.698%, and 1.093%. $C_{35}H_{57}O_{16}N$ is the theoretical (empirical) solid waste chemical compound, according to the findings of laboratory tests. The temperature in the three reactors was monitored between 28 and 30 °C during the first thirty days of the transition phase [Budihardjo et al., 2019].

Initial leachate characteristics

Testing of the initial characteristics of the leachate was carried out after waiting 40 days for the leachate to form from the three landfill bioreactors, which was referred to as week 0 of the measurements. The initial characteristics of leachate are reviewed through the parameters pH, temperature, TSS, COD, BOD_5, NH_4^+ – N, Fe, and Zn. Table 6 displays the initial leachate characteristics. The leachate temperature in the third landfill bioreactor is 25 °C, adjusted to room temperature. The temperature of the leachate is classified as the optimum temperature for bacterial growth, which is in the range of 25–30 °C [Tchobanoglous et al., 1993]. The initial leachate pH characteristics test findings were 7.04 (neutral) at 12% leachate recirculation variation, 5.79 (acid) at 6% leachate recirculation variation, and 5.76 (acid) in the variation without leachate recirculation. According to estimates made by Vesilind et al., (2002), the pH value of the leachate measured

Table 6. Initial leachate characteristic

Parameter	Recirculation 12%	Recirculation 6%	Without recirculation
pH	7.04	5.79	5.76
Temperature (°C)	25	25	25
TDS (mg/L)	13,340	23,640	21,160
TSS (mg/L)	2,700	2,500	1,800
COD (mg/L)	21,267	19,683.4	20,324
BOD_5 (mg/L)	6,765.3	8,256	7,740
NH_4^+-N (mg/L)	102	170	170
Fe (mg/L)	29.66	24.86	25.89
Zn (mg/L)	1.481	2.429	1.743

in the three landfill bioreactors prior to recirculation indicates that the waste degradation process has undergone an acidification stage, or the process of acid production, which typically happens at a pH of 4.7–7.7.

The COD test results also show the acidification stages in the three landfill bioreactors. The initial COD characteristic test results for leachate at 12% leachate recirculation variation were 21,267 mg/L; variation of 6% leachate recirculation is 19,683 mg/L; and in the variation without leachate recirculation, it is 20,234 mg/L, which is in the range of 1.500–71,000 mg/L [Vesilind et al., 2002]. An acidification phase is often indicated by an estimated NH4+-N value obtained before recirculation, with a concentration ranging from 2 to 1030 mg/L [Vesilind et al., 2002]. When leachate recirculation is varied by 12% in the landfill bioreactor, the NH4+-N value is 102 mg/L; when it is varied by 6%, it is 170 mg/L; and when it is varied without leachate recirculation, it is 170 mg/L. The high concentration of dissolved solids in the leachate is assumed to cause the high TDS value at the start of the process in the three landfill bioreactors. Meanwhile, a significant amount of bacterial growth and death in the form of suspended material from the ongoing waste degradation process is assumed to cause the high TSS value at the start. Based on the BOD_5 criterion, the amount of organic material in the leachate is relatively high. The decomposition of the composition of food waste, plastic, and paper, as well as the composition of metal waste in landfill bioreactors, is also assumed to be the source of the comparatively high quantities of heavy metals Fe and Zn [Long et al., 2011]. Heavy metal mobilization is believed to be caused by acidic pH conditions during the acidification step, which is also the reason for the high concentration of heavy metals.

Effect of leachate recirculation on leachate effluent quality

Organic waste made up 46.27% of this study's waste content, which impacted the amount of leachate generated. Because it breaks down quickly and contains much water, organic waste produces more leachate because more organic stuff is present [Yang et al., 2018]

This is shown by the daily leachate production of the three landfill bioreactors, which ranges from 50–100 L/day. The COD and BOD_5 parameters in leachate may rise in the presence of high levels of organic waste. The initial BOD_5 characteristic test results for leachate at 12% leachate recirculation variation were 6,765.3 mg/L; the variation at 6% leachate recirculation is 8.256 mg/L; and the variation at no leachate recirculation is 7,740 mg/L. Similarly, the initial COD characteristic test result for leachate at a variation of 12% leachate recirculation was 21,267 mg/L; at a variation of 6% leachate recirculation, it is 19,683 mg/L; and at a variation without leachate recirculation, it is 20,234 mg/L.

The leachate recirculation process was carried out in the first week after testing the initial characteristics of the leachate; the results showed that the concentrations of BOD_5 and COD continued to decrease. Because the BOD_5/COD ratio in Figures 5 and 6 is in the biodegradable range, which is 0.2–0.5, it is assumed that this is due to the organic material present in trash continuing to decrease as a result of decomposition by microbes under natural treatment circumstances [Samudro and Mangkoedihardjo, 2010]. The process by which microorganisms convert to CH_4 gas is assumed to be the reason for the lower COD concentration in leachate. Figure 4 displays the bioreactor landfill COD graph.

Based on the data, it can be concluded that landfill bioreactors without recirculation have the highest COD reduction efficiency (93.11%). In the meantime, the decrease in efficiency of the 12% leachate recirculation variation is higher than that of the 6% leachate recirculation variation, at 85.83% as opposed to 77.88%. According to several earlier studies, reactors with leachate recirculation stabilized faster and demonstrated noticeably faster degradation than reactors without recirculation. According to Francois et al., [2007] and Chan et al. [2002], leachate recycling can shorten the timeframe for acidogenesis and methanogenesis. However, there is a chance for regular contact between waste and leachate in landfill bioreactors that recirculate leachate, which could result in a leaching incident. In contrast, leachate washout curves with quick peaks occur in landfill bioreactors without recirculation, the reactor conditions are relatively dry, and there is little chance of waste and leachate interaction [Reinhart and Basel Al-Yousfi, 1996].

Apart from that, even though the solid waste composition is the same, the type of waste input is not entirely uniform. There may be a difference in the COD value of the leachate in each

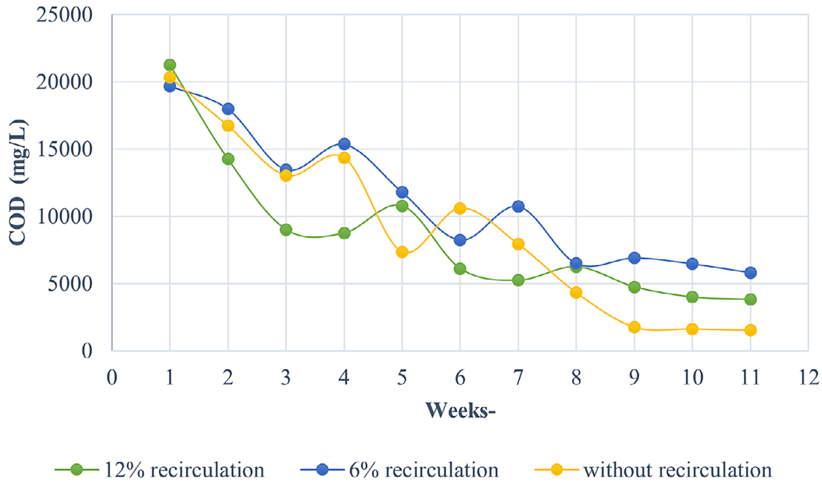

Figure 4. Bioreactor landfill COD graph

bioreactor. For instance, in a landfill bioreactor with a 12% leachate recirculation, rice may make up a larger portion of the food waste input; in a reactor with a 6% leachate recirculation, fruit will, and a reactor without recirculating leachate, may be meat. The following Figure 5 displays the bioreactor landfill BOD graph.

Effect of leachate recirculation on gas production

Leachate recirculation boosts gas generation in bioreactor landfills mainly by increasing moisture levels and enhancing microbial activity, which speeds up the waste degradation and production of methane and carbon dioxide gas. Ultimate analysis provides elemental composition (C, H, O, N, S) can be useful as part of a broader characterization to estimate methane potential and can indirectly indicate the potential for biodegradation since carbon and hydrogen content are essential for methane production. However, it does not specify how much of the carbon is readily biodegradable substrate versus inert or stabilized material [Singh et al, 2023; Efetobor et al, 2022; Top et al, 2019]. The solid waste sample in this study contains C, H, O, N evenly distributed, with percentages of 41.712%, 5.737%, 25.698%, and 1.093%, respectively with the empirical formula as $C_{35}H_{57}O_{16}N$. This empirical formula is used to determine the potential of methane and carbon dioxide gases. The stoichiometric equation to estimate the gas conversion mechanism that takes place:

$$C_{35}H_{57}O_{16}N + 12H_2O \rightarrow \\ \rightarrow 6CH_4 + 14CO_2 + NH_3 \quad (2)$$

The dry weight of waste used in ultimate analysis is 1 gram. According to [Tchobanoglous et al., 1993] the density of CH_4 is known to be 0.7167 g/L. Stoichiometric methane gas production is calculated by comparing the coefficient and relative molecular (Mr) values.

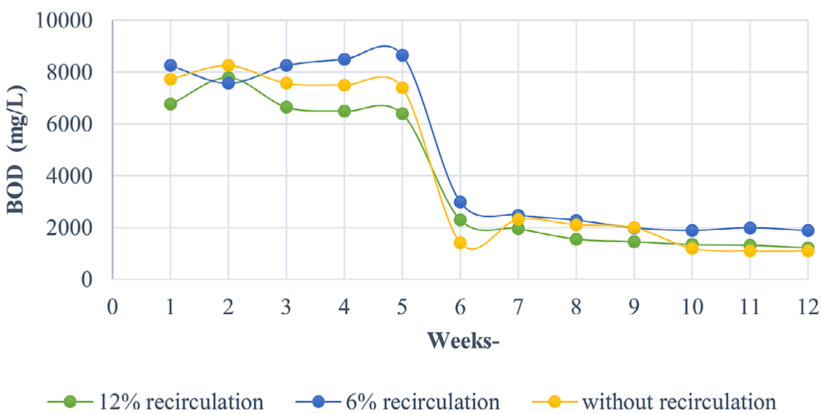

Figure 5. Bioreactor landfill BOD graph

$$Volume\ \mathrm{CH_4} = \frac{\mathrm{koef\ CH_4}}{1} \times \frac{\mathrm{Mr\ CH_4}}{\mathrm{Mr\ C_{35}H_{57}O_{16}N}} \times \frac{gram\ solid\ waste\ sample}{\rho\ \mathrm{CH_4}} \quad (3)$$

$$Volume\ \mathrm{CH_4} = \frac{5.88}{1} \times \frac{16.05}{747} \times \frac{1}{0.7176} = 0.176\ \mathrm{L} \quad (4)$$

Carbon dioxide gas (CO_2) production from waste is estimated using the chemical components of waste. It is known that CO_2 has a density of 1.96 g/L. By comparing the coefficient and relative molecular (Mr) values, the stoichiometric carbon dioxide gas generation can be calculated as follows.

$$Volume\ \mathrm{CO_2} = \frac{\mathrm{koef\ CO_2}}{1} \times \frac{\mathrm{Mr\ CO_2}}{\mathrm{Mr\ C_{35}H_{57}O_{16}N}} \times \frac{gram\ solid\ waste\ sample}{\rho\ \mathrm{CO_2}} \quad (5)$$

$$Volume\ \mathrm{CO_2} = \frac{14}{1} \times \frac{44}{747} \times \frac{1}{1.96} = 0.4207\ L \quad (6)$$

Based on the stoichiometry results, the estimated potential landfill gas from waste in the bioreactor landfill is 0.176 liters of methane and 0.4207 liters of carbon dioxide. The measurement for 76 days findings in Figure 6 indicates that the maximum methane gas production occurs at 6% recirculation, or 60 L/day, with an average output of 0.034382 L/day. Methane gas output averages 0.026372 L/day in a reactor with 12% recirculation (120 L/day). In the absence of recirculation, the average generation of methane gas is 0.03 L/day. In anaerobic bioreactor landfills, CO_2 is a major component of the landfill gas produced alongside methane. This CO_2 is generated during the anaerobic decomposition of organic waste by microorganisms. Specifically, in the methanogenesis phase, anaerobic microbes convert organic acids into CH_4 and carbon dioxide, typically resulting in landfill gas composed of roughly 40–60% methane and 40–60% carbon dioxide. The average carbon dioxide gas is displayed in Figure 7 at 6%, 12%, and without recirculation, with values of 0.295 L/day, 0.260 L/day, and 0.28 L/day, respectively.

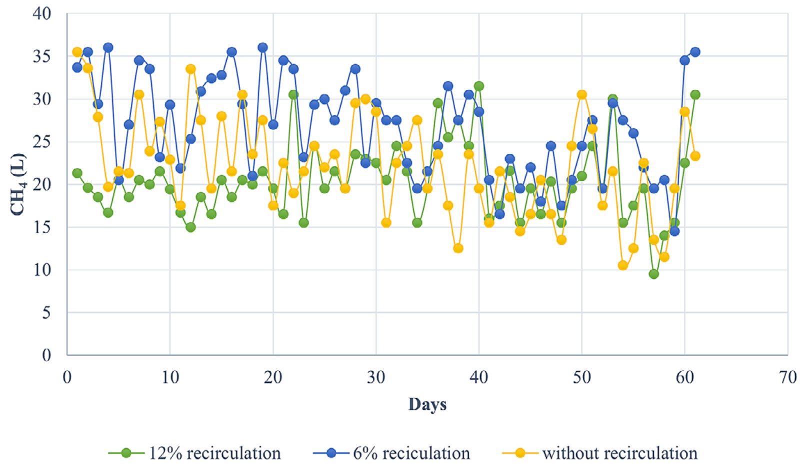

Figure 6. Bioreactor landfill methane production

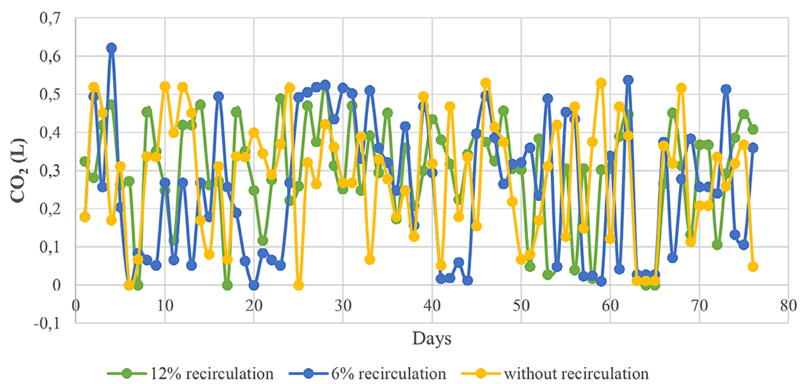

Figure 7. Bioreactor landfill carbon dioxide production

The results obtained from bioreactor landfill testing indicate a relatively low average daily gas production, attributable to the initial phase in which microbial populations are still establishing themselves. Continued monitoring is expected to reveal an increase in gas production as the system transitions into the active methanogenesis phase, characterized by peak methane generation that can persist from several months to a few years, contingent upon operational conditions and waste composition. Landfill gas can produce for roughly 10 to 20 years, with the active, high-rate methane production occurring primarily in the initial 5 to 10 years under optimized moisture and temperature conditions. Subsequently, the system enters a decline phase, during which gas generation diminishes gradually due to substrate depletion. The results show that leachate recirculation with 6% is better compared to without recirculation. This aligns with the theory that gas production is significantly faster and more intense than in traditional landfills, where gas production is slower and lasts longer due to lower moisture content and less controlled conditions [Lakshmikanthan et al., 2017].

The results show that the 12% leachate recirculation did not produce the highest methane and carbon dioxide. It is believed that the reactor with 12% leachate recirculation contained an inhibitor in the form of increased oxygen, which caused lower methane production compared to the other two reactors. Because the leachate recirculation was carried out more frequently, air was pumped back in, resulting in the reactor having an average oxygen content of 5.6% per day. Figure 8 illustrates that the reactor's oxygen level was higher than the allowed range of 0.1 to 1% for the anaerobic waste degradation process [Tchobanoglous et al., 1993]. Figures 6, 7, and 8 present methane production, carbon dioxide production, and oxygen inhibition in the bioreactor landfill, respectively.

Also, excessive or very high recirculation rates can lead to problems such as:

- accumulation of organic acids, causing acidification that inhibits methanogenic bacteria,
- build-up of toxic compounds like ammonia or chloride from the leachate, which suppress microbial activity,
- over-saturation reducing oxygen-limited anaerobic conditions or washing out microbes.

Therefore, while leachate recirculation generally enhances methane production by improving moisture and microbial activity, too high a recirculation rate disrupts microbial balance and slows methanogenesis, resulting in lower methane yields [Liu et al., 2018].

Besides inhibitors and recirculation rates, for an anaerobic bioreactor landfill to optimally degrade waste and transform it into landfill gas, sufficient substrate is necessary. Substrate availability can be assessed through proximate analysis, which includes moisture content and volatile matter. In this study, the moisture content for 12% leachate recirculation, 6% recirculation, and no recirculation were 56.12%, 52.18%, and 54.90%, respectively. Moisture content indicates the amount of water present, which affects microbial activity and substrate accessibility, and it is important to maintain optimal moisture levels (around 50% humidity) [Ana et al., 2024]. Meanwhile, the volatile matter for 12% leachate recirculation, 6% recirculation, and no recirculation were 82.75%, 83.25%, and 77.5%, respectively. Volatile matter represents the portion of waste that vaporizes when heated, mostly consisting of biodegradable organic compounds that serve

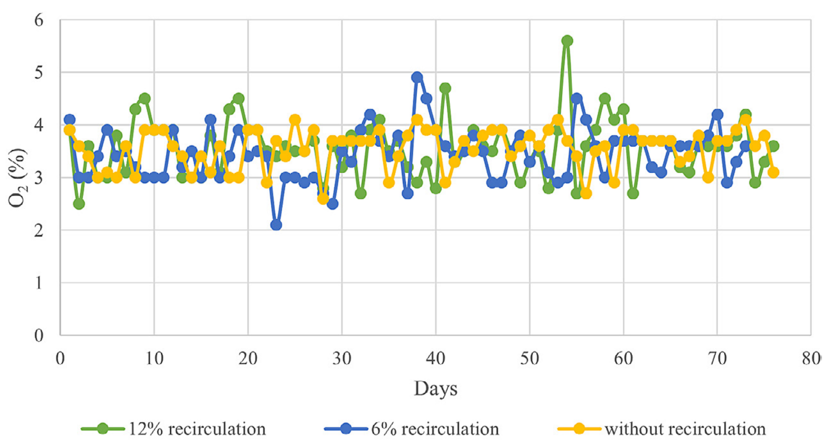

Figure 8. Bioreactor landfill oxygen inhibitor

as available substrates for microbes. The amount of biodegradable organic matter and the type of acids produced (like acetic, propionic, butyric acids) influence methane yield. Methanogens break down these acids to produce methane; depletion of substrates leads to a slowdown in methane formation [Grégoire et al., 2023]. The measurements of moisture and volatile content demonstrate that sufficient substrate availability exists to enable microorganisms to effectively transform waste material into landfill gas.

Effect of leachate recirculation on settlement

Leachate recirculation is anticipated to speed up waste degradation, which will manifest physically in the waste's settlement parameters. Leachate recirculation (12%, 120 L/day) settles at 16.61%, according to the measurement data; this is higher than 9.13% when recirculation (6%, 60 L/day) is used, and 4.02% when no recirculation is used. Prior to leachate recirculation, settlement measurements were conducted, and the results indicated that the decrease was not significant. The settling percentage increased further following the recirculation of the leachate at 12% and 6% variations. However, the settlement percentage decreased and backed up after the leachate was no longer injected. The phenomenon is believed to be caused by trapped gas in the waste matrix, which is challenging to release since saturation has sealed the pores, lifting the waste matrix. This phenomenon occurs in a reactor with 12% leachate recirculation, where a large amount of gas is thought to be trapped in the waste matrix. As a result, the measured settlement increases from 30.175 cm to 25.85 cm after the waste is lifted 4.325 cm. The average output of methane and carbon dioxide gas during leachate recirculation is 12% lower than variations of 6% and without recirculation, which further supports this. The following Figure 9 shows the settlement graph.

Effect of leachate recirculation on solid waste characteristics

The leachate recirculation process has an impact on waste moisture content. The percentage of moisture content in the waste matrix increased to 64.15 percent after 76 days of leachate recirculation at a variation of 12% (120 L/day). In the meantime, the moisture content percentage can reach 61.05% with 6% (60 L/day) of leachate recirculation. While this was going on, the moisture content dropped in the rector with no leachate recirculation. This result is in accordance with previous research which showed that the water content in the biorecator without leachate recirculation showed lower water content [Choi & Rhee, 2024]. According to Petchsri et al. (2006), the leachate cycling mechanism can enhance the water content of waste, hence creating more favourable physical, chemical, and biological conditions for the degradation process. Before leachate recirculation, the volatile content test findings were, respectively, variations in leachate recirculation of 12%, variations in leachate recirculation of 6%, and 82.75%, 83.25%, and 77.5% without recirculation. Waste can transform into several forms, including heat, compost, new microorganism cells, and gases like CO_2, CH_4, NH_3, and SO_2, due to the substantial volatile value at the beginning of the process [Tchobanoglous et al., 1993]. Following 76 days of leachate recirculation, recirculation 12% and recirculation 6% had volatile levels of 69.30% and 71.67%, respectively. In the

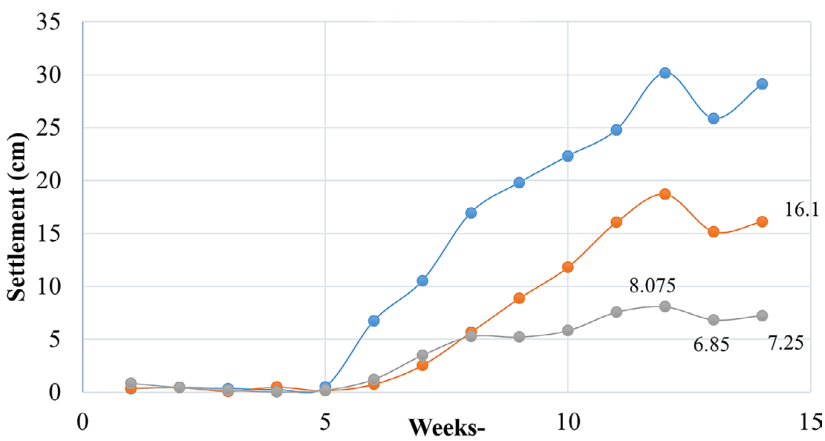

Figure 9. Settlement graph

meantime, 70.98% of the cases are without recirculation (control).

Organic components in solid waste have a potential biodegradability of 12%, 0.134 g/day. The measurement data, which show that recirculation 12% has a better COD flushing efficiency than recirculation 6%, which suggests that COD is turned into CH_4, further confirms this. The final waste test findings for the elements N, O, H, and C were 1.093%, 41.712%, 5.737%, and 25.698%, respectively, at the start of the process. Following leachate recirculation, the recirculation of the 12% final test results showed a decline compared to the other two reactors, particularly for C and H. Gasification is one of the characteristics that indicates biodegradation, and it is assumed that the recirculation of 12% organic material in the waste is turned into gas. Gasification is one of the characteristics that indicates biodegradation, and it is assumed that the R1 organic material in the waste is turned into gas. The final test findings indicate that the solid waste in recirculation 12% is suspected to have a faster biodegradation rate, even though the methane gas measurement values in recirculation 12% are lower than in recirculation 6% and without recirculation. Accordingly, it is believed that the reason the methane gas generated in recirculation 12% is supposedly hard to release into the atmosphere is that the waste conditions are getting more saturated, that it is packed with leachate, or that the pore space is getting more compressed because of recirculation. As a result, the rate at which liquid and gas pass through the system slows down, as shown by the very slow vertical permeability value. Another hypothesis is that the increasing compression of the waste pores causes the gas generation in recirculation 12% to migrate horizontally.

The results of the solid waste permeability test before leachate recirculation, with a 12% recirculation rate, were 4.509 cm/hour (medium). Meanwhile, recirculation 6% is in the slow category with a speed of 0.381 cm/hour. After experiencing leachate recirculation for 76 days, the permeability rate at recirculation was 12%, and recirculation at 6% became very slow, especially at 12%, with a leachate recirculation volume of 12% (120 L/day) to 0.008067 cm/hour. It is suspected that the waste condition is becoming more saturated because the pore space is becoming more compressed, so the rate of passage of liquids and gases is becoming slower. This is thought to cause gas production in recirculation 12% to be lower than recirculation 6% because the pore space is increasingly compressed, making it challenging to release gas into the atmosphere.

Effect of leachate recirculation on biodegradation rate and settlement using MANOVA

Multivariate analysis of variance, or MANOVA, is used to compare many dependent variables since, at their core, phenomena in life are influenced by multiple factors. One independent variable and several dependent variables are present in this study test, which employs a one-way multiparameter MANOVA test. Situation – impact of leachate recirculation on settling and biodegradation rate (methane and COD gas characteristics). The leachate recirculation volume, which is 120 L/day, 60 L/day, and 0 L/day, is the only independent variable. In the meantime, the dependent variables are settlement and the biodegradation rate (methane and COD gas characteristics). The hypothesis used to test differences in the effect of treatment on several response variables:

- H_0: $\tau_1 = \tau_2 = \tau_3 = 0$ – leachate recirculation volume does not influence biodegradation rates (methane and COD gas parameters) and settlement.
- H_1 = there is at least one $\tau_1 \neq 0$.

Criterion	Test Statistic	F	DF Num	DF Denom	P
Wilks'	0.09672	20.677	6	56	0.000
Lawley-Hotelling	6.13889	27.625	6	54	0.000
Pillai's	1.21277	14.892	6	58	0.000
Roy's	5.56380				
s = 2 m = 0 n = 13					

Figure 10. One-way MANOVA result

Figure 10 shows the results of one-way MANOVA. The test focused on is Wilks' Lambda. The $F_{0,05}$ value is 20.677, while the P value or significance obtained is 0.000. The significance value obtained is < 0.05, so H_0 is rejected or there is an influence of leachate recirculation volume on the rate of biodegradation (methane and COD gas parameters) and settlement.

CONCLUSIONS

Waste breakdown can be accelerated and stabilized through experiments using landfill bioreactors. Stabilizing the waste and speeding up the decomposition process are two benefits of operating a landfill bioreactor that circulates leachate back into the waste matrix. This study's waste decomposition rate is represented through the COD parameters of leachate, methane gas, and waste settlement. Leachate recirculation effectively lowered toxicity and organic load, as indicated by COD values. Recirculation volume 12% (120 L/day) can reduce the organic load by up to 85.82%. Concurrently, recirculating leachate lowers the organic load by 77.87% at a rate of 6% (60 L/day). The measurement results show that the highest methane gas production is at 6% recirculation, R2 (60 L/day), with an average methane gas production of 0.034382 L/day. Meanwhile, at 12% recirculation (120 L/day), the average methane gas production is 0.026372 L/day. It is suspected that there is an inhibitor in the form of O_2, which is higher in 12% recirculation, because the leachate recirculation process is carried out more frequently. Apart from that, it is also suspected that because the 12% recirculation leachate volume is relatively high, it results in a saturated waste condition, the pore space in the waste is compressed, and the permeability rate becomes slower. Hence, the gas is difficult to release. The results of the waste permeability test before leachate recirculation, R1, are classified as moderate with a rate of 4.509 cm/hour. After experiencing leachate recirculation for 76 days, the permeability rate at 12% recirculation became very slow, at 0.008067 cm/hour. The measurement results show that leachate recirculation in 12%, 120 L/day, has a settlement rate of 16.61%, compared to 6%, 60 L/day, which is 9.13%, and without recirculation (0%), which is 4.02%. MANOVA test was carried out to identify the effect of leachate recirculation on biodegradation rates (methane and COD gas parameters) and settlement. MANOVA test results show that leachate recirculation volume influences the rate of biodegradation (methane and COD gas parameters) and settlement. Suggestions for further research are to examine more deeply the internal and external factors that can influence the progress of the degradation process in landfill bioreactors. It is hoped that these factors can be minimized so that the degradation process in the landfill bioreactor runs optimally.

Acknowledgment

The authors are grateful to the PPMI ITB for funding support.

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