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Evaluation of Leachate Recirculation Volume on Pollutant Removal and Biogas Production : a Case Study of Piyungan Landfill, Yogyakarta

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ABSTRAK

Resirkulasi lindi merupakan salah satu jenis pengolahan biologis on-site dengan mengembalikan lindi yang terbentuk pada tumpukan sampah. Keuntungan resirkulasi lindi antara lain dapat meningkatkan biodegradasi sampah, meningkatkan efisiensi penurunan BOD dan COD pada lindi, dan meningkatkan produksi CH_4. Penelitian ini bertujuan untuk mengevaluasi resirkulasi lindi yang berbeda volume dalam menurunkan kadar polutan pada lindi dari TPA Piyungan serta meningkatkan produksi biogas dari sampah perkotaan. Air indi diambil dari Instalasi Pengolahan Lindi di TPA Piyungan, Bantul, Yogyakarta. Sampel sampah segar dikumpulkan dari TPS 3R Purwoberhati, Kalasan, untuk merepresentasikan komposisi sampah TPA Piyungan. Penelitian ini melibatkan tiga bioreaktor anaerobik: R0 (kontrol), R1 (12 L/hari), dan R2 (24 L/hari). Resirkulasi lindi selama 35 hari menunjukkan kecenderungan penurunan konsentrasi BOD dan COD pada R1 dan R2. Konsentrasi pada R0 tidak dapat diukur karena tidak ada lindi baru yang dihasilkan. Jika dibandingkan antara konsentrasi awal dan akhir, efektivitas penurunan BOD mencapai 98,4% pada R1 dan 92% pada R2. Sedangkan efektivitas penurunan COD mencapai 99,4% pada R1 dan 96,7% pada R2. Terdapat pula penurunan signifikan pada logam berat (Fe, Cr, dan Cd). Selama proses resirkulasi lindi, CH_4 hanya terukur di R2 pada hari ke-21 dengan konsentrasi 0,23%. Selain itu, hanya gas CO_2 yang terukur. Resirkulasi lindi dalam penelitian ini dapat mengurangi kadar pencemar dalam lindi. Namun, durasi eksperimen yang singkat membatasi evaluasi terhadap metanogenesis; oleh karena itu, peningkatan pembentukan CH_4 tidak dapat terkonfirmasi.

***Kata kunci*:** Resirkulasi Lindi, BOD, COD, Biogas

ABSTRACT

Leachate recirculation is an on-site biological treatment method in which the generated leachate is returned to the waste mass. Its advantages include enhancing waste biodegradation, improving the removal efficiency of biochemical oxygen demand (BOD) and chemical oxygen demand (COD) in leachate, and promoting methane (CH_4) production. This study aimed to evaluate the effect of different leachate recirculation volumes on reducing pollutant concentrations in leachate from the Piyungan Landfill and enhancing biogas production from municipal solid waste. Leachate samples were collected from the Leachate Treatment Facility at the Piyungan Landfill, Bantul, Yogyakarta. Fresh waste samples representing the composition of municipal solid waste at the Piyungan Landfill were collected from the Purwoberhati 3R Waste Processing Facility (TPS 3R Purwoberhati), Kalasan. Three anaerobic bioreactors were operated: R0 (control), R1 (12 L/day), and R2 (24 L/day). Leachate recirculation over a 35-day period resulted in a decreasing trend in BOD and COD concentrations in R1 and R2. Pollutant concentrations in R0 could not be measured because no new leachate was generated. Based on the comparison between the initial and final concentrations, BOD removal efficiencies reached 98.4% in R1 and 92.0% in R2, while COD removal efficiencies reached 99.4% and 96.7%, respectively. Substantial reductions in heavy metal concentrations (Fe, Cr, and Cd) were also observed. During the recirculation process, methane (CH_4) was detected only in R2 on day 21 at a concentration of 0.23%, whereas carbon dioxide (CO_2) was detected throughout the experiment. The results demonstrate that leachate recirculation effectively reduced pollutant concentrations in leachate. However, the relatively short experimental duration limited the evaluation of methanogenesis; therefore, an increase in methane (CH_4) production could not be confirmed.

***Keywords*:** Leachate recirculation, BOD, COD, Biogas

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1. INTRODUCTION

Landfilling is still the mainstay of solid waste management in Indonesia. Kaza et al. (2018) reported that Indonesia manages municipal solid waste through open dumping (10%), unspecified landfilling (69%), and recycling (7%). According to the waste management hierarchy, landfilling is the final disposal option after implementing 3R (Reduce, Reuse, and Recycle) activities at the source. As a result, many landfills in Indonesia have exceeded their capacity or have already reached full capacity, yet they continue to receive domestic waste. This situation is mainly due to the limited availability of land for new landfill sites (Darwati, 2009).

The Piyungan Landfill is a regional landfill in Yogyakarta Province, serving three regencies, namely Yogyakarta City, Sleman Regency and Bantul Regency. According to data from the Yogyakarta Provincial Environmental Agency (DLH), the landfill received an average of 733 tons of waste per day in 2022. In mid-2022, the old cell at The Piyungan Landfill was closed, and a new disposal cell was developed adjacent to it. The old cell covers an area of 10 ha and consists of two zones, namely Zone A and Zone B. Landfill cell structuring and soil covering have been completed, and the waste pile has reached an elevation of 140 m above sea level (Wibowo, 2024).

The closure of the old landfill cell does not necessarily eliminate the potential for pollution. According to the Regulation of the Minister of Public Works No. 13 of 2013, environmental quality monitoring must be carried out for up to 20 years after landfill closure because leachate and methane continue to be generated during the post-closure period. Widhiananto (2022) found that leachate from the Piyungan Landfill exceeded the quality standards for BOD, COD, TSS, TDS, and Fe, with concentrations of 780 mg/L, 3,812.5 mg/L, 315 mg/L, 9,190 mg/L, and 9.6525 mg/L, respectively. The high organic matter content in the leachate is caused by the inability of the leachate treatment facility at the Piyungan Landfill to properly treat leachate from the waste pile.

Leachate treatment at landfill is generally carried out off-site. This approach requires high operational and maintenance costs, including operators, equipment, and energy consumption (Priyambada & Oktiawan, 2020). Another way to treat leachate is on-site or in-situ treatment by returning the generated leachate to the landfill. At the same time, this process transforms the waste mass into a bioreactor. This method is known as leachate recirculation (Patil et al., 2024).

Leachate recirculation is a biological treatment method in which leachate is recirculated over the waste mass to enhance waste biodegradation and methane (CH_4) production (Bilgili et al., 2007). Research conducted by Priyambada, et al. (2021) showed that leachate recirculation increases the reduction efficiency of BOD (Biological Oxygen Demand) and COD (Chemical Oxygen Demand). Another study conducted by Farastika (2017) showed that the leachate BOD and COD improved after recirculated to the pile of fresh waste and old waste at the Batu Layang Landfill, Pontianak with the efficiency of reducing BOD up to 79.3% and reducing COD up to 71%. In addition, the formation of biogas occurred on the 14th day until the end research on fresh waste recirculation. The potential for the formation of biogas through leachate recirculation can be a source of new renewable energy (Ahmadifar et al., 2016).

The composition of waste between one district and another will differ due to seasonal factors, socio-economic levels, lifestyles, and other factors (Damanhuri & Padmi, 2016). Several studies on leachate recirculation to solid waste from various regions in Indonesia have been conducted. Ali et al. (2020) observed the treatment of leachate recirculation in solid waste taken from the Blang Bintang Aceh landfill. Putri (2014) studied the effect of salinity recirculation, which showed that salinity inhibited the degradation of solid waste taken from the Ngipik landfill. Syafrudin et al. (2011) observed the effects of aeration and leachate recirculation on organic solid waste collected from the Jatibarang landfill. According to Sponza and Ağdağ (2004), using an optimal recirculation volume enhances the reduction of COD and VFA and supports effective methane production. However, excessively large volumes can reduce the buffering ability of the system and hinder methanogenic processes. A study on leachate recirculation in Piyungan landfill waste has been conducted by Kasam et al. (2016). Using different ages of landfill waste, the study shows that lysimeters with leachate recirculation have an effect on the rate of BOD and COD reduction in both fresh and mixed waste compared to lysimeters without recirculation (Kasam et al., 2016). However, the effect of different leachate recirculation volumes on fresh solid waste from Piyungan landfill is not yet known. Therefore, in this study, leachate recirculation was carried out with two different leachate volume variations calculated from the waste bed volume of the Piyungan landfill (Chugh et al., 1998). The study used 15% and 30% of the waste volume in the landfill simulation reactor. Thus, this study aims to evaluate the effect of different leachate recirculation volumes in reducing pollutant levels in leachate from Piyungan landfill and increasing biogas production of municipal solid waste.

2. RESEARCH METHODOLOGY

2.1. Materials

The synthetic solid waste applied in this study was designed to represent waste composition of Piyungan Landfill. The composition samples consist of organic waste (56%), paper (15%), plastic (24%) and other waste in the form of metal, glass and textile (5%). This composition was based on the municipal solid waste composition of Yogyakarta Province reported in the National Waste Management Information System

(SIPSN) of the Indonesian Ministry of Environment and Forestry in 2023. The fresh solid waste sample was collected from the Purwoberhati 3R Waste Processing Facility (TPS 3R Purwoberhati), Kalasan. The leachate was taken from Leachate Treatment Facility in Piyungan Landfill, Bantul, Yogyakarta.

2.2. Experimental Procedures

Three sets of landfill simulation bioreactors were used in this study. All bioreactors were operated under anaerobic conditions. The reactors were made of blue plastic drums with a diameter of 38 cm and a height of 81 cm. Each bioreactor was equipped with an identical landfill area, a leachate collection and recycling system, and a gas sampling port. Leachate recirculation was performed manually. Before loading the waste, a layer of gravel approximately 5 cm thick was placed at the bottom of each bioreactor to facilitate leachate filtration. Next, 10 kg of waste was loaded into each bioreactor.

The experimental design included three bioreactors: R0 as the control without leachate recirculation, and R1 and R2 with leachate recirculation rates of 12 L/day and 24 L/day, respectively. The leachate was recirculated at flow rates of 400 mL/min in R1 and 800 mL/min in R2 for 30 min each day. Recirculation was conducted for 35 days. Each reactor was operated for 56 days.

Table 1. Research Variables

Independent Variables	Dependent Variables	Control Variables
Synthetic solid waste	• BOD • COD • Heavy metals • Biogas concentration	• Waste weight • Leachate volume • Leachate flow rate

Table 2. Experiment Design

No	Code	Conditions During the Research	Leachate Volume
1	R0	No recirculation (control)	0
2	R1	Leachate recirculation of 15% from the waste bed volume	12 L/day
3	R2	Leachate recirculation of 30% from the waste bed volume	24 L/day

2.3. Analytical Method

The leachate was monitored for 35 days. Leachate quality was analyzed every 7 days for BOD and COD. Meanwhile, heavy metal concentrations (Cr, Cd, and Fe) were analyzed at the beginning (day 0) and at the end of each reactor's operation (day 25 for R1 and day 35 for R2). The final leachate analysis was performed on day 25 for R1 and day 35 for R2 because the available leachate volume in each reactor was insufficient to continue sampling beyond those time points. All laboratory tests were performed according to Standard Methods.

The gas produced from the reactor was collected using a syringe. Gas sampling was conducted weekly from day 21 to day 56. The gases were then analyzed using Shimadzu Gas Chromatography.

3. RESULT AND DISCUSSION

3.1. The Effectiveness of Leachate Recirculation in Removing Pollutant Levels

Leachate recirculation showed a decreasing trend in BOD concentration in R1 and R2. However, the pollutant concentrations in R0 could not be measured as no new leachate was generated during 35 day-experimental period. This is likely because the waste in R0 did not have sufficient moisture content to reach field capacity and produce leachate. Field capacity is another parameter related to water content and is important in a landfill. This parameter can be defined as the maximum water content that waste can hold against gravity under conditions of free downward drainage (Sughosh & Sivakumar Babu, 2021). The leachate recirculation process provides the appropriate moisture that accelerates the growth of microorganisms and increases the rate of waste degradation (Šan & Onay, 2001; Zhang et al., 2023). Therefore, the primary role of R0 was to represent the natural anaerobic degradation process without leachate recirculation rather than to provide a direct comparison of leachate quality. Since no additional moisture was applied, the waste did not reach field capacity and thus did not generate sufficient leachate for routine analysis. Unlike R1 and R2, which continuously received recirculated leachate, R0 relied solely on its initial moisture content throughout the experiment.

Leachate recirculation in R1 and R2 was conducted for 35 days. During the leachate recirculation, there was a daily decrease in leachate volume due to some leachate being retained in the waste pile. As a result, by day 25, the leachate in R1 was exhausted, so leachate monitoring ceased on day 21. Meanwhile, in R2, leachate volume remained at the end of the experiment on day 35, allowing leachate data for day 28 to be obtained. At the mid-stage of landfilling, the waste is dominated by complex organic substances that are more difficult to decompose, causing the biochemical reaction of microorganisms to this organic waste to weaken, resulting in a gradual decrease in leachate volume in both bioreactors (Wu et al., 2025).

Figure 1 illustrates the curve of BOD concentration change each week. At the start of the experiment, the BOD was 2,628 mg/L. On the 7th day, there was an increase in BOD concentration in both reactors. However, the BOD concentration decreased again on the 21st and 28th days. A significant decrease occurred in R2 on the 28th day with a value of 1,940 mg/L.

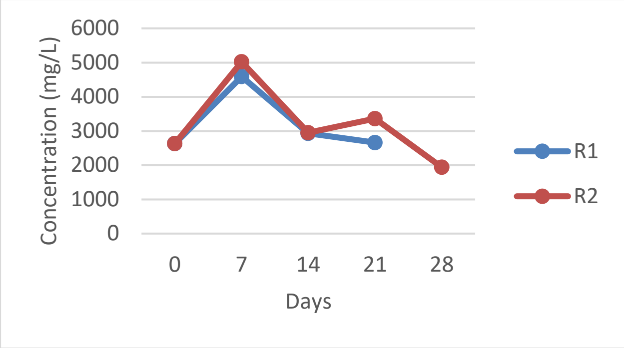

Figure 1. BOD Concentration Change of R1 and R2

The study results showed that the BOD reduction patterns in R1 and R2 were largely similar, as indicated by the overlapping trends in their graphs. However, in general, both reactors showed a tendency of BOD reduction. This result corresponds to research conducted by Farastika (2017) and Priyambada et al. (2021), which also showed that leachate recirculation leads to a decrease in BOD in leachate.

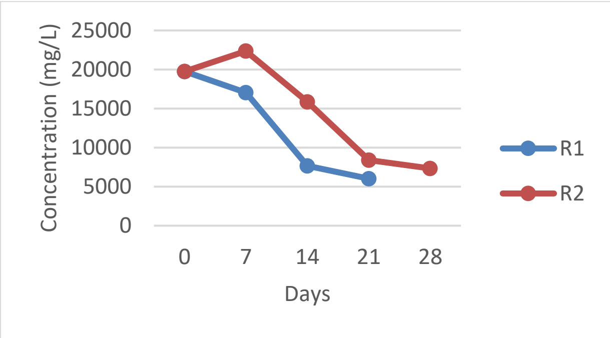

Figure 2. COD Concentration Change of R1 and R2

Figure 2 presents the curve of COD concentration change in R1 and R2, tested every 7 days. Unlike the BOD curve, the COD curve showed a tendency of decreasing concentration. At the beginning of the experiment, the COD concentration was 19747 mg/L. Subsequently, there was an increase in COD concentration in reactor R2 on the 7th day. However, the COD concentration continued to decrease until the 21st day for reactor R1, reaching 6,018.8 mg/L, and the 28th day for reactor R2, reaching 7,331.3 mg/L. The initial increase in COD also corresponds to the research conducted by Bilgili et al. (2007) and Farastika (2017). An increase in COD indicates that fresh organic waste undergoes hydrolysis without changing the COD value (Priyambada & Oktiawan, 2020).

The weekly monitoring of BOD and COD in leachate showed that leachate recirculation, in general, can reduce the levels of contaminants in the form of BOD and COD in leachate. When compared to the quality standards, the final concentrations of BOD and COD do not meet the standards set by Permen LHK No. 59 of 2016, which are 100 mg/L for BOD and 300 mg/L for COD. This occurs because the organic material has not yet reached a stabilization period. Bilgili et al. (2007) found that the anaerobic degradation process of waste occurs more slowly than the aerobic degradation. Then, Bilgili et al (2007) reported that COD removal in anaerobic bioreactors with recirculation reached 87% on the 250th day. Other studies showed that BOD removal in anaerobic reactors with leachate recirculation reached 83% on day 161 by Ma et al. (2021) and 86,75% on day 160 by Ahmadifar et al. (2016). Due to the limited duration of the experiment, BOD and COD removal may have continued to improve if the leachate recirculation period had been extended. Nevertheless, the results of this study show that leachate recirculation effectively reduced BOD and COD concentrations under the experimental conditions.

Besides weekly analyses, leachate samples were also analyzed at the beginning and end of the experiment for BOD, COD, and the heavy metals Fe, Cr, and Cd. Leachate on day 0 showed a BOD concentration of 2628 mg/L, COD of 19748 mg/L, Fe of 90.8 mg/L, Cr of 0.16 mg/L, and Cd of 0.12 mg/L. In R1 at the end of the experiment, on the 25th day, the BOD concentration was 41.3 mg/L, COD was 116 mg/L, Fe was 11.2 mg/L, Cr was 0.16 mg/L, and Cd was 0.12 mg/L. Meanwhile, in R2 at the end of the experiment, on the 35th day, the BOD concentration was 208 mg/L, COD was 660 mg/L, Fe was 1.5 mg/L, Cr was 0.11 mg/L, and Cd was 0.09 mg/L. These data are presented in Figure 3.

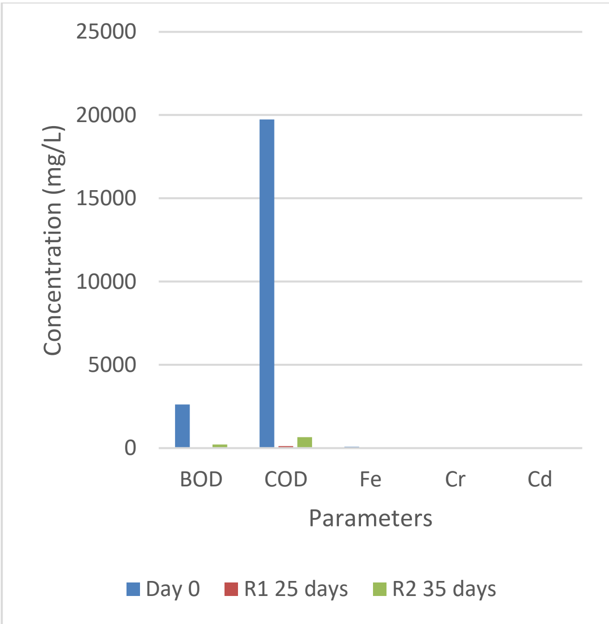

Figure 3. Leachate Quality of R1 And R2 at the Beginning and End of the Experiment

According to Figure 3, the leachate quality differs from the results of weekly analyses, particularly in BOD and COD concentrations. When comparing the initial and final concentrations, the reduction effectiveness for BOD reached 98.4% for R1 (25 days) and 92% for R2 (35 days). The reduction effectiveness for COD reached 99.4% for R1 and 96.7% for R2.

When compared to weekly testing, the removal percentage shows the same trend, namely that the removal percentage of R1 is higher than that of R2. Therefore, under the experimental conditions of this study, a leachate recirculation volume of 15% appeared to be more effective than 30% for promoting organic matter degradation. Sponza and Ağdağ (2004) found that when the recirculation volume increased from 13% to 30%, there was a decrease in methane production and a negative effect on COD removal in the leachate. They attributed this to excess leachate causing an accumulation of VFA, which inhibited the methanogenic phase. Although the final leachate analysis for R1 was conducted on day 25 due to the limited availability of leachate, R1 had already achieved higher BOD and COD removal efficiencies than R2, whose final analysis was performed on day 35. These findings further support the assumption that a 15% leachate recirculation volume provides more favorable conditions for organic matter degradation than a 30% recirculation volume under the experimental conditions of this study.

There was also a decrease in heavy metal concentration. The effectiveness of Fe reduction for R1 and R2 was 87.7% and 98.3%, respectively. This can be explained by the fact that the mechanism of Fe removal in anaerobic landfills occurs through the main mechanisms of precipitation and/or adsorption on waste as the leachate is recirculated through the waste (Ahmadifar et al., 2016). Sorption and precipitation that occur at higher pH values are effective for Fe, possibly as siderite ($FeCO_3$) (Bilgili et al., 2007). In R2, there was a decrease in Cr and Cd concentrations of 31.25% and 25%. Conversely, in R1, there was an increase in Cr and Cd concentrations at the end of the experiment. The concentrations of Cr and Cd metals in the leachate were low because the metals prefer to attach to solids (sorption) or precipitate as sulfide/carbonate minerals (precipitation), and this process is very strong at neutral-alkaline pH (Bilgili et al., 2007). Or this could be due to the leachate recirculation process increasingly flushing out dissolved materials in the waste pile containing Cr and Cd (Lee et al., 2023).

3.2. Evaluation of Leachate Recirculation in Increasing Biogas Production

The decomposition process will result in the production of biogas consisting of CO_2, CH_4, H_2, N_2, and H_2S. The anaerobic decomposition of waste involves four stages starting with hydrolysis, followed by acidogenesis, acetogenesis, and finally methanogenesis (Damanhuri & Padmi, 2016). Leachate recirculation treatment in anaerobic reactors leads to the degradation of organic waste. The observation of waste degradation was carried out visually at the end of the experiment. Figure 4 illustrates the condition of the waste after the completion of reactor operation.

(a) R0 (b) R1 (c) R2

Figure 4. Comparison of Waste Settlement in R0, R1, and R2

Figure 4 shows that the waste height in the control reactor (R0) remained unchanged throughout the experiment. This indicates that the degradation of organic waste in R0 occurred very slowly. In contrast, the waste height in the leachate recirculation reactors (R1 and R2) was visibly lower than that in R0. Similar results were reported by Hussein and Ibrahim (2023), who found that anaerobic reactors with leachate recirculation operated for 480 days achieved a waste reduction of 51.7%, compared with 43.4% in reactors without leachate recirculation. These findings suggest that leachate recirculation accelerates the degradation of organic waste. However, waste settlement could not be quantified in the present study, which represents one of its limitations.

During anaerobic decomposition, organic waste is converted into soluble organic compounds in the leachate and eventually into biogas. During the leachate recirculation process, methane (CH_4) was detected only in R2 on day 21 at a concentration of 0.23%. In contrast, carbon dioxide (CO_2) was detected throughout the experiment. The CO_2 concentrations measured in R0, R1, and R2 are presented in Table 3.

Table 3. CO_2 Concentration Produced During the Experiment

Days	R0 (%)	R1 (%)	R2 (%)
21	5.11	3.45	6.13
28	3.7	1.89	4.16
35	5.26	3.03	7.08
42	3.53	0.82	1.07
49	3.59	1.49	3.27
56	3.4	1.26	2.97

Table 3 presents the CO_2 concentrations resulting from the leachate recirculation experiment. Some literature mentions that leachate recirculation can increase the CH_4 biogas concentration. However, this study could not confirm this due to the absence of methanogenesis in anaerobic decomposition in all reactors. The low methane production in all reactors was considered additional evidence of washout, indicating the inability of the system to develop an active methanogenic population and enhance the waste stabilization (Šan & Onay, 2001). Methanogenic bacteria are highly sensitive to environmental factors such as acidic conditions or presence of ammonia and have a slow growth rate (Sponza & Ağdağ, 2004). Another limitation of this study is the absence of pH and volatile fatty acids (VFAs) monitoring throughout the experiment. These parameters strongly influence microbial activity and the transition from acidogenesis to methanogenesis (Abdeljaber et al., 2025). VFAs are important intermediate compounds in anaerobic degradation leading to biogas production (Gao et al., 2025). Their accumulation during the acidogenesis phase is accompanied by elevated COD concentrations and a decline in pH. As anaerobic microorganisms become more active, COD concentrations decrease due to continued organic matter degradation, while pH gradually returns to near-neutral conditions during methanogenesis. This phase is favored at pH values ranging from 6.5 to 8.2 (Ağdağ & Sponza, 2005; Shen et al., 2025). Temperature is also a critical parameter for monitoring the waste biodegradation process. Organic waste decomposes most efficiently under mesophilic conditions (Patil et al., 2024). Therefore, future studies should include routine measurements of pH, VFAs, and temperature to better explain the biological mechanisms governing leachate recirculation performance.

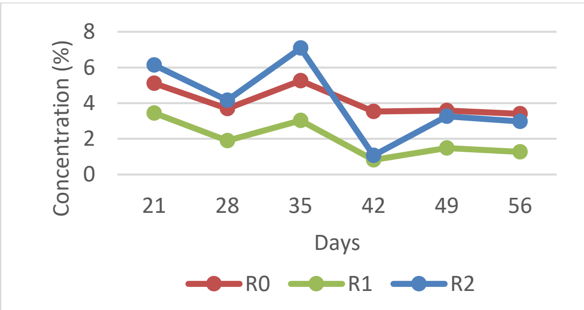

Figure 5. CO_2 Production in R0, R1, and R2 During the Experiment

Figure 5 shows a comparison of CO_2 concentrations in reactors R0, R1, and R2. It can be seen that the lowest CO_2 concentration occurs in reactor R1 with a similar pattern of change to R0 and R2. The low amount of biogas formed in R1 could be due to the conversion of organic waste through the liquid phase being more dominant than the gas phase. This is evidenced by the highest BOD and COD removal effectiveness in R1 compared to the others. When the anaerobic bioreactor enters the methanogenesis and gas production stage, it will be accompanied by a decrease in COD (Ahmadifar et al., 2016). Meanwhile, in R0 (without recirculation), the main mechanism of decomposition is through the conversion of organic waste into biogas. In R2, the highest CO_2 concentration occurred on day 35. Then the concentration decreased on day 42 and increased again on days 49 and 56. Overall, CO_2 gas production in this study indicates biological decomposition of organic waste, supported by evidence of a decrease in waste height in the reactor at the end of the experiment.

4. CONCLUSION

This study demonstrates that leachate recirculation effectively reduced pollutant concentrations in leachate from Piyungan Landfill. BOD removal efficiencies reached 98.4% in reactor R1 and 92% in reactor R2, while COD removal efficiencies were 99.4% for R1 and 96.7% for R2. Based on the experimental conditions of this study, a recirculation volume of 15% (12 L/day) showed better performance in reducing BOD and COD than a recirculation volume of 30% (24 L/day). In contrast, heavy metal removal was more pronounced at 24 L/day. However, because heavy metal concentrations continued to decrease throughout the experimental period, the process had not yet reached a stable condition. Therefore, a definitive optimum recirculation rate based on heavy metal removal could not be established within the duration of this study.

Leachate recirculation also enhanced the degradation of organic waste in both R1 and R2 when compared with the control reactor (R0). However, this study was unable to verify an increase in methane production. Most of the biogas generated throughout the experiment was identified as CO_2. Because the experiment was conducted for only 35 days, the results mainly represent the early stage of anaerobic degradation. Longer operational periods are required to evaluate complete waste stabilization and methane generation. The absence of pH, temperature and VFA measurements in this study limits the ability to confirm whether methanogenesis was inhibited by acid accumulation. Future studies should include routine monitoring of these parameters to better explain the transition from acidogenesis to methanogenesis.

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