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Improvement of leachate quality and waste stabilization in pilot-scale bioreactor landfills containing geotextile filters and sewage sludge

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ABSTRACT

In many developing countries, there has been growing interest in bioreactor landfills for municipal solid waste (MSW) management. This research study has been conducted for comparing leachate characterization and waste stabilization in simulated pilot-scale anaerobic bioreactor landfills. Four pilot-scale reactors were constructed and operated for 540 d. This study aimed to show whether a pilot-scale bioreactor containing sewage sludge mixed with MSW, with a geotextile filter in its drainage layer, and with recirculating leachate, could improve leachate quality and waste stabilization in a landfill. Bioreactor R1 comprised MSW and sewage sludge, while bioreactor R2 was the same as R1 but with a geotextile-1 (GT-1) filter fitted. R3 contained no sludge but only MSW and GT-1 fitted, while R4 contained no sludge but only MSW and two layers of geotextile filter (GT-2 and GT-3). All reactors were operated with leachate recirculation, simulating bioreactor landfills. The results showed that the chemical oxygen demand (COD) half-lives of leachate from the reactors were approximately 8, 7, 9, and 10 months for R1, R2, R3, and R4, respectively. By the end of the study, the waste in R2 and R4 was more stable, with 66% and 65% reductions in volatile solids, respectively. Reactor R2, which contained MSW, sewage sludge, and one-layer geotextile (GT-1), provided higher stabilization of MSW and shorter COD half life than the other reactors.

Keywords: Municipal solid waste; Bioreactor landfill; Geotextile; Anaerobic biodegradation; Leachate treatment

1. Introduction

Sanitary landfilling is one of the most economic and common ways for managing municipal solid waste (MSW) disposal in the world. Despite using methods such as recycling, reuse and incineration to reduce the amount of MSW entering landfill, landfilling will continue to be the dominant method of MSW disposal in the coming years. Landfill, preceded by separation and recovery, can be the most suitable waste management method for developing countries [1]. The common problems associated with managing MSW result from poor implementation of waste segregation at source, low operational efficiency of waste transport systems, environmental and health risks of the leachate and inefficient recycling systems [2–4]. In many developing countries, financial restrictions and inadequate regulations or their inadequate enforcement can lead to poor planning or operation of MSW management [5]. For developed countries, the amount of waste needing disposal has declined significantly, and at the same time the proportion that could be recovered and recycled has increased [6]. On the other hand, rapid economic and population growth as well as changes in consumption patterns has caused waste generation to continue to increase [6].

Leachate is produced in landfills, as a result of water or rainfall moving through the solid waste mass, and may contain contaminants in solution or suspension produced by chemical or biological reactions. The amount and composition of leachate produced is usually site specific, but

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the leachate characteristics are closely related to the waste composition, the landfilling method, the characteristics of the water entering the landfill, the permeability of the landfill cover, and the physico-chemical reactions taking place in the landfill. Leachate produced in a landfill must be collected and treated before it is discharged from the landfill site. Some leachate treatment methods include a sequential batch reactor coupled with ultrafiltration [7], an anaerobic dynamic membrane bioreactor [8], a two-stage anaerobic membrane bioreactor [9], coagulation and flocculation [10,11], chemical precipitation [10], and an anaerobic multistage treatment system [12].

Landfills can be operated as bioreactors, exploiting microbial activity, especially when the rate of waste decomposition needs to be accelerated, for example, when the waste moisture content is very low. Besides increasing the moisture content in the landfill, recirculated leachate can create a better environment for the microorganisms responsible for waste decomposition. Operating landfills as bioreactors not only accelerates waste stabilization but also improves the leachate quality. Improvement of leachate quality can be affected by reactants that are distributed within the MSW [13]. Increasing the moisture content through leachate recirculation or water addition is a key parameter to boost the biological reactions in bioreactor landfills [14]. In some bioreactor landfill studies, co-disposal of sewage sludge showed a positive effect on the MSW stabilization process [15–17]. Pohland and Kim [18] reported that in-situ leachate treatment, prior to its ultimate disposal, accelerated the rate of waste conversion and stabilization. The principal microbial populations in bioreactor landfills are analogous to those in anaerobic processes, but are more evident because of the massive reaction zones and longer contact times, especially in the presence of leachate recirculation [18]. Therefore, higher overall treatment rates and greater landfill gas generation are accomplished with leachate recirculation, because biodegradable leachate compounds are retained and not lost due to elution from the system [18]. Another benefit of bioreactor landfills is that, as a result of increased waste decomposition, additional treatment volume is gained.

The lab-scale version of the system tested in this current study investigated the effect of geotextile filter on leachate quality [19–21]. The dimensions of the lab-scale reactors were 1 m high and 30 cm diameter. The current study is an expansion on the lab-scale trials, intended to investigate any leachate quality improvement in bioreactor landfills with geotextile filters on a pilot-scale level over a 540 d period. The current study included four reactors, with dimensions of 3.5 m height and 80 cm diameter. In this study, two of the four reactors were filled with MSW and municipal sewage sludge (for increasing the moisture content), while the previous lab-scale study treated only MSW. Also, this pilot-scale study used different types of geotextile filters in terms of apparent opening size, permeability, and thickness, while the first study used only one type of geotextile filter.

This bioreactor study simulated and investigated bioreactor landfills that are closed, but still produce leachate and landfill gas. The purpose of this study was to investigate the process of improving leachate quality and increasing waste stabilization rate, on a larger scale. To achieve that, the effects on leachate quality and waste stabilization of adding different types of geotextile filters and of adding sewage sludge to the MSW were studied in simulated bioreactor landfills. When compared with granular materials such as sand and gravel for filtering, geotextiles have the advantage of being manufactured, which provides better control of the desired physical and hydraulic properties. Geotextiles are cost effective, easy to install and are made from durable materials. The use of geotextile material in waste treatment systems has been studied by several researchers. For instance, Silva and Palmeira [17] used vertical panels of non-woven geotextiles as filters for raw leachate from a landfill and observed that geotextile filters improved values for leachate parameters, with a reduction of up to 42% in COD. It was also reported significant COD reduction in experimental domestic wastewater cells where non-woven geotextiles were used as filters in drainage systems [22]. Geotextile filters have been also used for stormwater and wastewater treatment [23]. Despite the studies presented in the literature using geotextile to improve leachate quality, the current study of a geotextile filter used in in-situ leachate treatment in a pilot-scale bioreactor landfill containing sewage sludge will be, to the best of our knowledge, the first such study.

2. Materials and methods

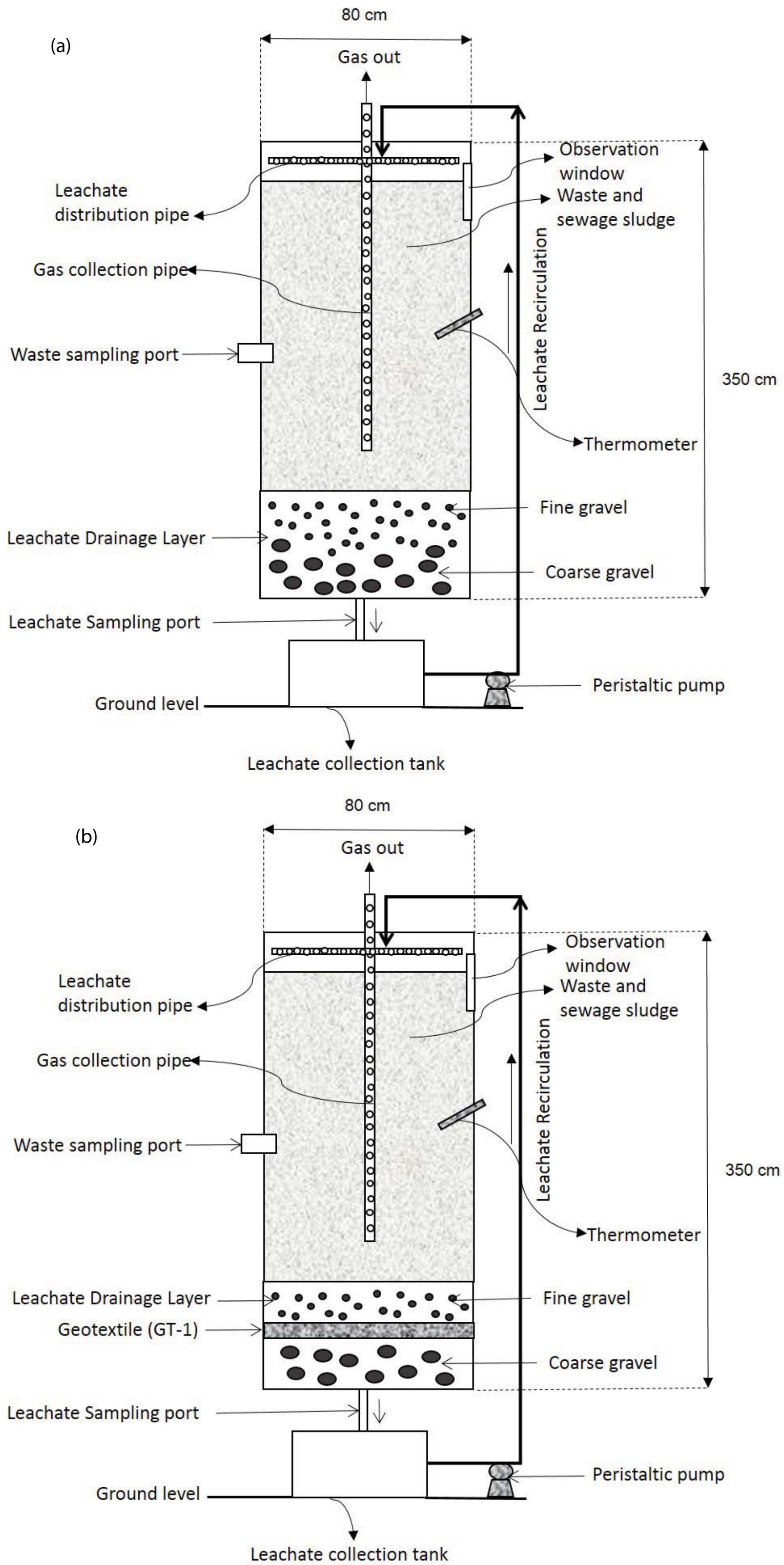
2.1. Materials

The feed waste material was obtained from a compost plant operated by Istanbul Metropolitan Municipality. The MSWs were collected from the outlet of the 80 mm-diameter rotary screen at the entry to the compost plant. The size of waste components was manually reduced to smaller than 5 cm. The MSW sample waste comprised (by wet weight) food waste (67.5%), paper (17.5%), plastics (6.5%), glass (1%), metal (1%), textile (2%), stone (0.5%), and inert material (4%). The initial moisture content of the MSW was 49.9%. The total volatile solids (VS) from MSW components were 80% of total solids (TS).

2.2. Bioreactor configuration

To simulate bioreactor landfills, four pilot-scale reactors, made of stainless steel, were constructed, 3.5 m high, with a diameter of 80 cm (1.75 m^3 volume). The reactors were equipped with three main ports for leachate drainage, waste sampling and leachate sampling and recirculation (Fig. 1a [R1], Fig. 1b [R2], Fig. 1c [R3], and Fig. 1d [R4]). The reactors consisted of two main compartments: (i) the upper compartment was designed to hold the mass of waste, and (ii) the lower compartment consisted of the drainage layer.

Unlike reactor R1, reactors R2, R3, and R4 contained geotextile filters in their drainage layers to evaluate their potential to reduce the COD removal time in the leachate. The leachate produced in the reactors was collected after passing through a specifically designed drainage layer. The total depth of the drainage layer was 15 cm, and two types of gravel of different sizes were used at different levels in the layer. The coarse gravel (d_{50} = 12.5 mm) was placed at the bottom of the drainage layer to 10 cm depth, and the fine gravel (d_{50} = 10 mm) was placed at the top, to 5 cm depth. In R2 (GT-1), R3 (GT-1), and R4 (GT-2 [upper] and GT-3 [below]), the geotextile filters were inserted into the drainage layers.



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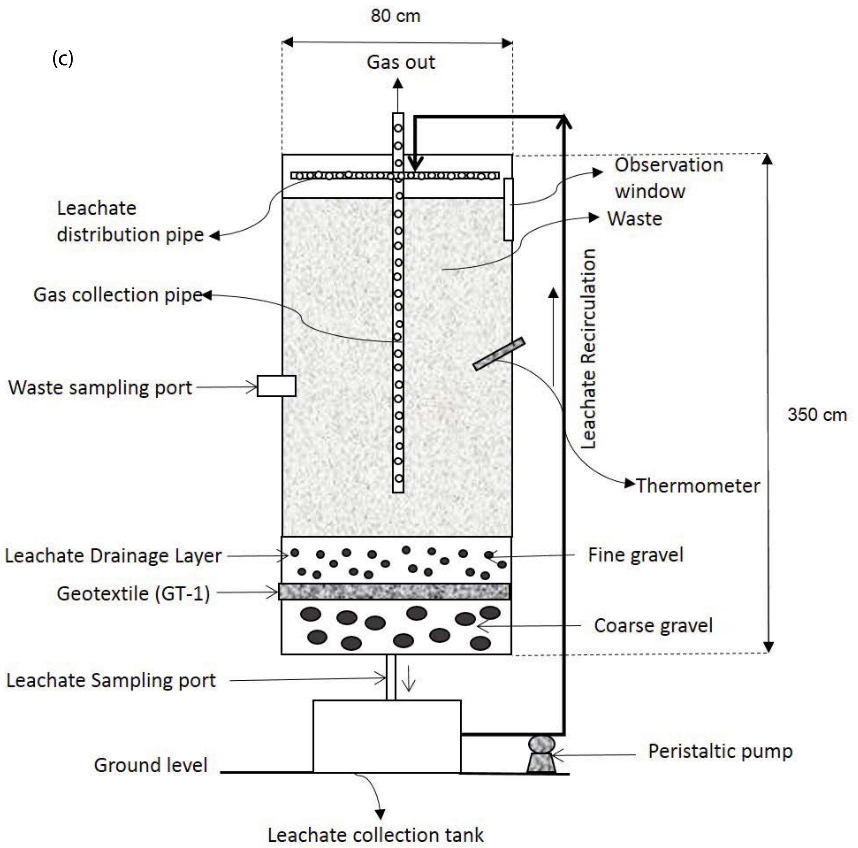

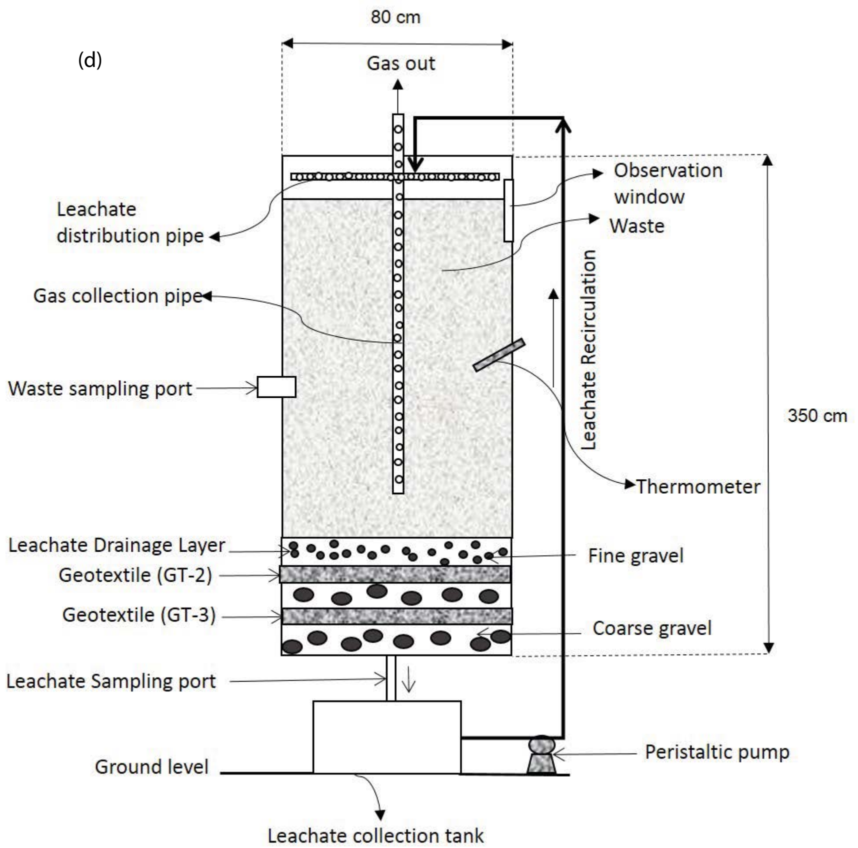

Fig. 1. (a) Schematic diagram of reactor R1, (b) R2, (c) R3, and (d) R4.

The technical specifications of the geotextile filters are given in Table 1. The geotextile filters used in this study differed from each other in terms of manufacturing method (needle punch vs. needle punch heat bonded), material type (polypropylene and polyester), apparent opening size (pores), thickness, and permeability.

The bottom of each reactor was constructed to allow the leachate to drain into the gravel layer. The leachate produced in the reactors passed through the drainage layer and was collected in the 50 L exterior leachate tank. This exterior tank was made of transparent PVC and had an opening for analysis, using probes. It also had a volumetric scale to measure the leachate volume produced. Peristaltic pumps were run 3 h d^{-1} to recirculate the leachates to the reactors. The recirculated leachates were distributed from the top of the reactors by using an evenly perforated pipe, with approximately 80 pores with 5 mm-diameter. For the collection and removal of biogas, a perforated PVC pipe, 300 cm high, 5 cm diameter, was placed vertically in each reactor.

2.3. Operation of reactors and experimental start-up

The operation of the reactors is summarized in Table 2. The reactors were placed in an isolated room and operated at 35°C ± 2°C. Anaerobic processes usually operate at either mesophilic (30°C–40°C) or thermophilic (50°C–60°C) temperatures. Anaerobic processes at high temperature allow a shorter retention time and give higher efficiency in the degradation of organic matter compared with digestion at mesophilic temperatures. In this study, the reactors were kept near 33°C–37°C to maintain mesophilic conditions. The ambient temperature was measured by a digital room thermometer, which showed the maximum and minimum measured temperatures. The current values were monitored to ensure that the ambient temperature was between the desired values. Each reactor was filled with 900 kg MSW, and the waste was compacted to a density of 750 kg m^{-3} and the total volume was calculated to be 1.2 m^3. On top of the waste material, a layer (2–3 cm) of 4 mm diameter coarse sand was placed to allow for the uniform distribution of the recirculated leachate. The operation of the bioreactors was started by closing all the ports and lids to make sure that the reactors were both airtight and watertight. In the first month of the operation, 8 L distilled water was added every week to the reactors by using the peristaltic pumps to simulate rainfall. This 8 L volume was determined based on the amount of precipitation that the local region received yearly. In all reactors, all the produced leachates were recirculated to the body of waste every day. Simulated bioreactors were operated for 540 d.

2.4. Analytical methods

The composition of the solid waste was determined by separating each type of waste component in the feedstock. After separating food, paper, textile, glass, metal, plastic and stone from the mixed waste, each component was weighed separately. Subsequently, the percentage of each waste component was determined. Analyses for total carbon (TC), total Kjeldahl nitrogen (TKN), ammonium nitrogen (NH_4–N), total phosphorus (TP), and other solid waste parameters were determined by standard methods [24]. The composition of waste is described in Table 3. The sewage sludge

Table 1
Properties of geotextile filters used in the study

Type and model	Name	Thickness (mm)	Apparent opening size (μm)	Permeability (L m^{-2} s^{-1})	Material	Production method
GT-1	TenCate TS50	1.91	112	113	Polypropylene (PP)	Needle-punched
GT-2	IzoTeknik 200	1.4	84	60	Polyester (PET)	Needle-punched Heat-bonded
GT-3	GeoTeknik 200	1.9	110	95	Polypropylene (PP)	Needle-punched Heat-bonded

Table 2
Operation modes of reactors

Parameters		R1	R2	R3	R4
MSW amount	kg	900	900	900	900
MSW volume	m^3	1.2	1.2	1.2	1.2
MSW density	kg m^{-3}	750	750	750	750
Sewage sludge amount	kg	45	45	No	No
Water addition (for 4 weeks)	L $week^{-1}$	8	8	8	8
Leachate recirculation	Yes/No	Yes	Yes	Yes	Yes
Recirculation frequency	Times $week^{-1}$	7	7	7	7
Geotextile layer	Yes/No	No	Yes (GT-1)	Yes (GT-1)	Yes (GT-2 and GT-3)

Table 3
Composition (%, by weight) of the waste

Organic content	Paper	Textile	Glass	Metal	Plastic	Stone	Other
67.5	17.5	2.0	1.0	1.0	6.5	0.5	4.0

(76% moisture content) used in this study was composed of 24% TSs, of which 69% was VS and 31% was fixed solids.

Leachate was collected on a weekly basis. The leachate samples were taken from the reactors and stored at 4°C prior to analysis. Analyses of total dissolved solids (TDS), conductivity, pH, TKN, SO_4^{2-}, oxidation–reduction potential (ORP), COD, total alkalinity, NH_4^+, total volatile fatty acids (tVFA), and chloride ions (Cl^-) were performed by standard methods [24]. The 5 d biochemical oxygen demand (BOD_5) parameter was determined using the OxiTop (WTW, Weilheim, Germany) method. Metals were determined by using inductively coupled plasma optical emission spectroscopy (ICP-OES Optima 7000DV).

After the completion of the experiment, the drainage layers of R2, R3, and R4 were removed from the upper compartment to recover the geotextile filters. The geotextiles were removed from the reactors and air dried overnight. Then, duplicate samples of ~1 cm^2 area were taken from the geotextiles for use as samples of which to take scanning electron microscopy (SEM) pictures. The geotextile samples were sputter-coated in gold before SEM analysis, which was conducted with a Philips XL30S-FEG (France) instrument.

After the 540 d of operation, waste samples were collected from each reactor. After separating glass, plastics, and metals from the waste samples, VS analysis was performed for evaluating waste biodegradation in each reactor.

3. Results and discussion

The simulated pilot-scale reactors were monitored throughout the study to investigate the effect of the sewage sludge, leachate recirculation and geotextile filters on the leachate quality and waste stabilization. For this purpose, all the results from the leachate quality, waste analysis and microbial biomass detection analysis are given in this section.

3.1. Stabilization of MSW

To determine the degree of stabilization of the waste, the solid waste samples were taken from each reactor and analyzed for physical and chemical parameters. Table 4 shows the properties of the feed waste for each reactor before and after the study. The initial pH value of the MSW was 6.18, while the final pH values in all three reactors were above 8. The content of VS on a dry weight basis relative to the initial MSW was 80%. VS contents of the MSW from each reactor were analyzed by loss on ignition at 550°C. After 540 d of operation, final VS contents were 33.3%, 27%, 31.5%, and 27.7% for R1, R2, R3, and R4, respectively. The highest carbon loss was observed in R4, while the highest nitrogen loss was in R1. Reactors R2 and R4 exhibited higher losses of VS than the other reactors. It can thus be asserted that reactors with geotextile filters achieved slightly higher VS reductions, especially in R2 and R4. The addition of sewage sludge did not seem to have a significant effect on nitrogen and carbon reductions. In a similar study, VS reductions were reported between 37.13% and 67.60% for anaerobic bioreactor landfills [25]. Investigation of bioreactor landfills under semi-aerobic, anaerobic, and aerated conditions showed reductions of VS varying from 25.3% to 61.3%, TOC from 38.5% to 46.5% and TKN from 21.6% to 27.8% [26]. In a study on biodegradation of MSW in bioreactors, VS reductions were reported to be between 28.9% and 68.1% [27]. Maximum TC and VS reduction rates in this study were 66%, while the previous lab-scale study showed TC reduction of 52% and VS reduction of 44%. This study also showed similar results to those studies cited above.

3.2. Mass balance of carbon and nitrogen

Determination of the mass balance of carbon allows evaluation and quantification of how carbon is distributed among the main forms of emissions, leachate and landfill gas, and the residual waste. Table 4 shows the mass balance of the waste before and after the study. The mass balance findings on the final characteristics of the waste indicated that the proportions of carbon relative to dry waste were 14.6%, 14.8%, 15.4%, and 13.3% for R1, R2, R3, and R4, respectively. The proportions of nitrogen relative to the final dry waste were less than 1% for all reactors. The lost carbon was

Table 4
Physical and chemical properties of MSW before (0 d) and after (540 d) reactor treatment

	Dry waste	Moisture content	pH	C	N	VS	TC	TN	TP
	kg	%		kg	kg	%	mg kg^{-1}	mg kg^{-1}	mg kg^{-1}
Initial MSW	450.9	49.9	6.18	175	8.7	80	388,000	19,500	3,148
R1 final	238.8	63.1	8.95	35	1.4	33.3	145,854	5,776	1,023
R2 final	276.4	58.1	9.07	41	2	27	147,657	7,259	838
R3 final	278	58.8	8.57	43	2.2	31.5	153,236	8,058	541
R4 final	256	59.9	8.82	34	2.1	27.7	131,163	8,309	865

probably released into leachate and biogas, while the lost nitrogen was mainly released into leachate. The unreleased carbon fraction might have been deposited as carbonates in the reactors [15,28] and was converted to CH_4 and CO_2 gases during the operation.

Nitrogen is an important nutrient for the growth of microorganisms. However, excess levels of nitrogen in the landfills can lead to the accumulation of ammonia, which can cause toxicity and hinder the digestion process. It was reported that a C:N ratio of 20–35 would be optimal for the biodegradation of municipal organic waste [29]. In this study, the initial C:N ratio was around 20, while the final C:N ratios were 25, 20.5, 19.5, and 16.2 for R1, R2, R3, and R4, respectively, which indicates that the C:N ratios remained at optimal levels during the study, except for R4. It can be assumed that most of the nitrogen was either released into leachate or remained in the solid waste since the amount of N_2 in biogas is negligible. The sum of TKN and NH_4 concentrations in leachate was higher at the end of the study than at its initiation, which indicates that almost all of the nitrogen was released into the leachate. However, carbonaceous compounds were released both into the leachate (as COD, tVFA, CO_2, etc.) and into the biogas since the main composition of the biogas is CH_4 and CO_2.

3.3. Leachate characterization

The volume of recirculated leachate varied for all reactors. The average recirculated leachate volumes per ton waste dry matter (t_{DM}) during the study were between 130 and 135 L t_{DM}^{-1} d^{-1} for all reactors. In a similar pilot study, Sponza and Ağdağ [30] reported leachate recirculation rates of 621–1,750 L t_{DM}^{-1} d^{-1}, while, in a column study, it was reported a leachate recirculation rate of 38.6 L t_{DM}^{-1} d^{-1} [31]. The difference between the recirculation rates from the different studies was probably due to the different initial moisture contents and compositions of the waste.

3.3.1. pH

In general, leachate from a stabilized landfill will have a higher pH than that from a recently established landfill. Since leachate pH is related to the volatile fatty acids (VFAs) and alkalinity contents of the system, the initial low pH in young landfills is due to the high concentration of VFAs being produced during the acid phase. Cations such as NH_4^+ tend to increase the pH, while the accumulation of VFAs tends to decrease the pH [32].

In this study, the leachate pH values were monitored twice a week. As can be seen in Fig. 2, the leachate pH values as the reactors began to operate started at near 6.0. Then, they decreased to below 6 for all reactors and were maintained at this level until methanogenic conditions occurred. This initial decline was mainly due to accumulation of VFAs in the reactors. In the reactors, during the fermentation and conversion to VFAs, pH dropped to acidic levels due to the accumulation of organic acids. As these organic acids were being consumed by the methane bacteria, the pH levels increased to optimum conditions for methanogenesis. R2 reached a neutral pH first (day 227), followed by R1 (day 260), R3 (day 274), and then R4 (day 309). This increase in pH was mainly due to the consumption of volatile organic acids by the microorganisms. The final pH values for all reactors were around 8 by the end of the study. The optimal pH levels for acidic bacteria were reported to be between 5.5 and 6.5, while those of methane bacteria lie between 6.8 and 7.4 [33]. Some studies

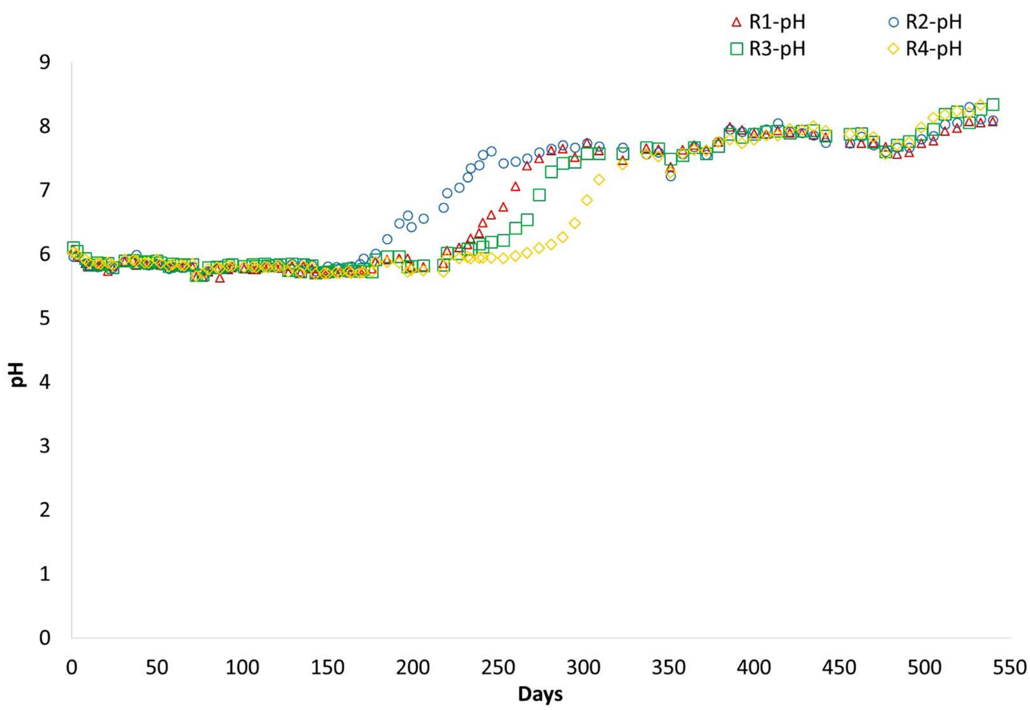

Fig. 2. pH variations in reactors.

have reported similar pH values in aerobic and anaerobic bioreactor landfills [25,34–36].

3.3.2. Oxidation–reduction potential

ORP is an important parameter in wastewater treatment and negative values must be maintained for the anaerobic processes to operate effectively. While high redox potentials (aerobic conditions) result in rapid biodegradation [34,37], the optimum ORP value for methanogenesis (anaerobic conditions) usually ranges from –100 to –300 mV [38–40]. The ORP tests need to be carried out immediately after sampling [41]. In this study, once the available oxygen in anaerobic reactors was consumed by the aerobic microorganisms, ORP values started to decrease, indicating that degradation had shifted from the acidogenic phase to the methanogenic phase. The point of inflection of decreasing ORP matched that of the point of inflection of increasing pH in all reactors, at around day 200 (Fig. 3). While the ORP for R2 reached about −150 mV on day 192, the ORP for R1 reached −145.5 mV on day 241, R3 reached −145.5 mV on day 241, and R4 reached −138.6 mV on day 274. The final ORP values late in the methanogenic phase were around –400 mV for all reactors, after which they started to increase gradually as the methanogenic phase ended.

3.3.3. TDS and conductivity

Kylefors and Lagerkvist [42] reported that the concentration of TS is expected to decrease as the leachate shifts from the acidogenic phase to the methanogenic phase. The range of TDS concentrations in landfill leachate in the literature is between 2 and 60 g L^{-1} [43]. Yuen [41] reported that the TDS concentration does not change markedly. In this study, there was a small decrease in TDS during the transition period from the acidic phase to the methanogenic phase (Fig. 4). The TDS concentrations varied between 11.36 and 18.43 g L^{-1} for all reactors. Final TDS concentrations were 17.4, 16.77, 15.32, and 13.34 mg L^{-1} for R1, R2, R3, and R4, respectively. Similar TDS values were reported in literature [3,42,44].

The changes in leachate conductivity were very similar to those in TDS. Conductivity is a parameter that is used as an indicator of dissolved inorganic species or total ion concentration and is a measure of the solution's ability to convey an electric current. Conductivity values increased in the first days of the operation. This may be associated with the ions washed out by the leachate recirculation. The values of conductivity varied from 22.5 to 37.3 ms cm^{-1} for all reactors (Fig. 5). A range of similar conductivity values are reported in literature [3,44,45].

3.3.4. Metal analysis

Some toxic metals such as lead are easily leachable from MSW to leachate. Plastics and batteries are major contributors of lead to solid waste. Other less toxic metals such as chromium can originate from metal plating and occur in inks and paints. Nonferrous metals such as lead, zinc, and copper are found in appliances and consumer electronics. The concentrations of Zn, Cr, Cu, and Pb were monitored throughout the study. However, only concentrations of lead are presented in Fig. 6, since it is more toxic than the others. During the study, the concentrations of metals in leachate were reasonably low. However, the metal concentrations were high at the early stages of the study because of the higher solubility of metals due to the increased levels of organic acids in leachate. The concentrations of Cu and Zn were slightly above 2 mg L^{-1} for all reactors. As the pH increased to above a neutral level, the metal concentrations decreased as a result of reduced solubility. The final concentrations of Zn, Cr, Cu,

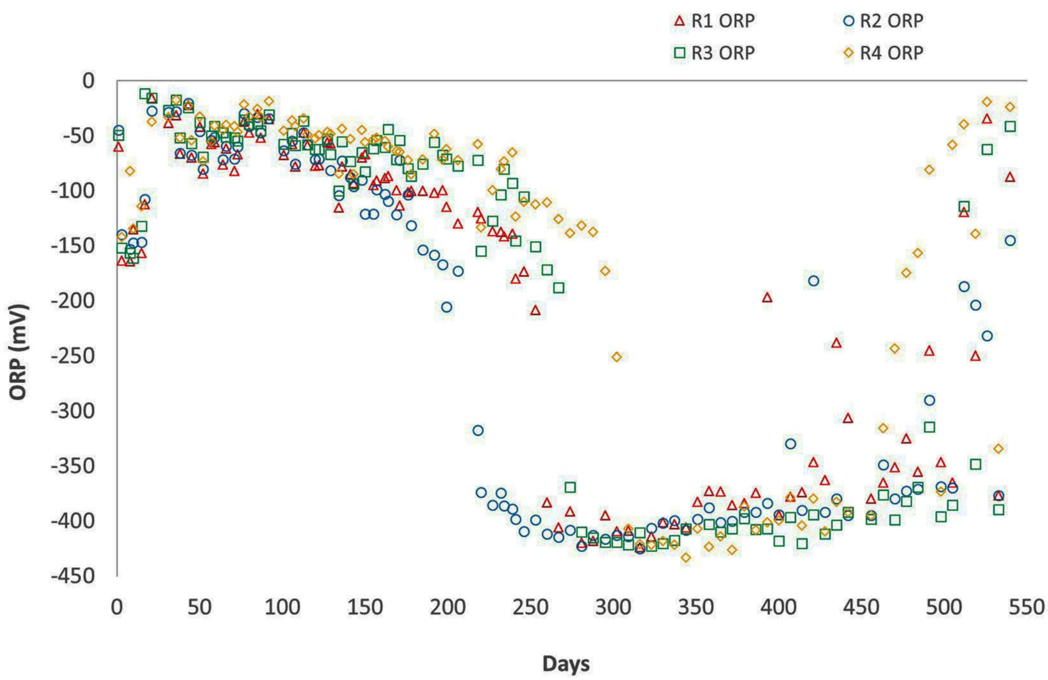

Fig. 3. ORP changes in reactors.

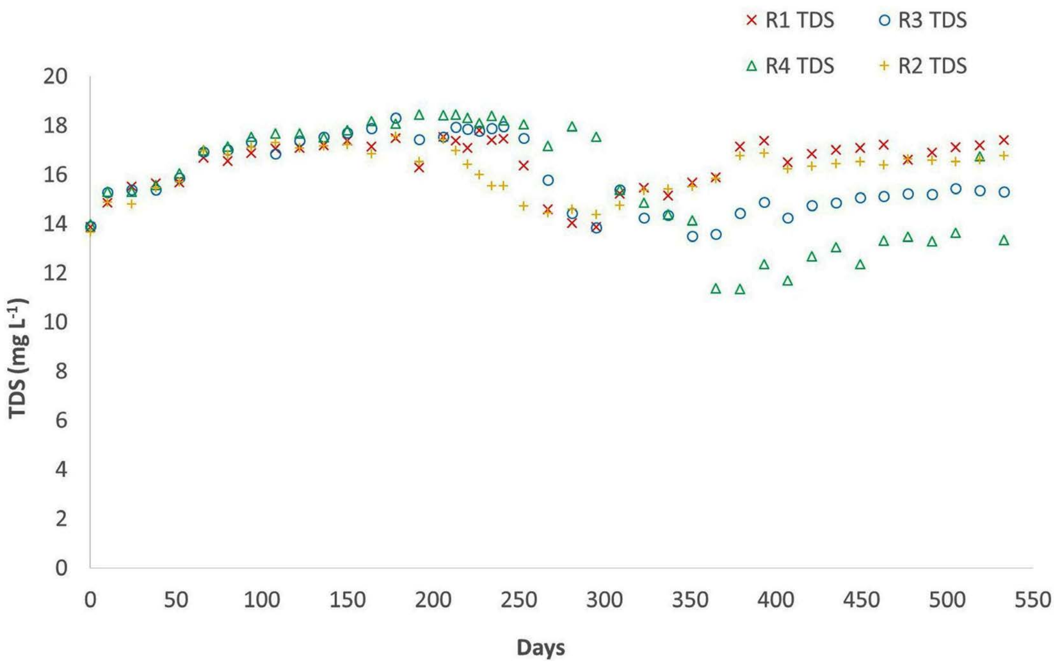

Fig. 4. TDS variation in reactors.

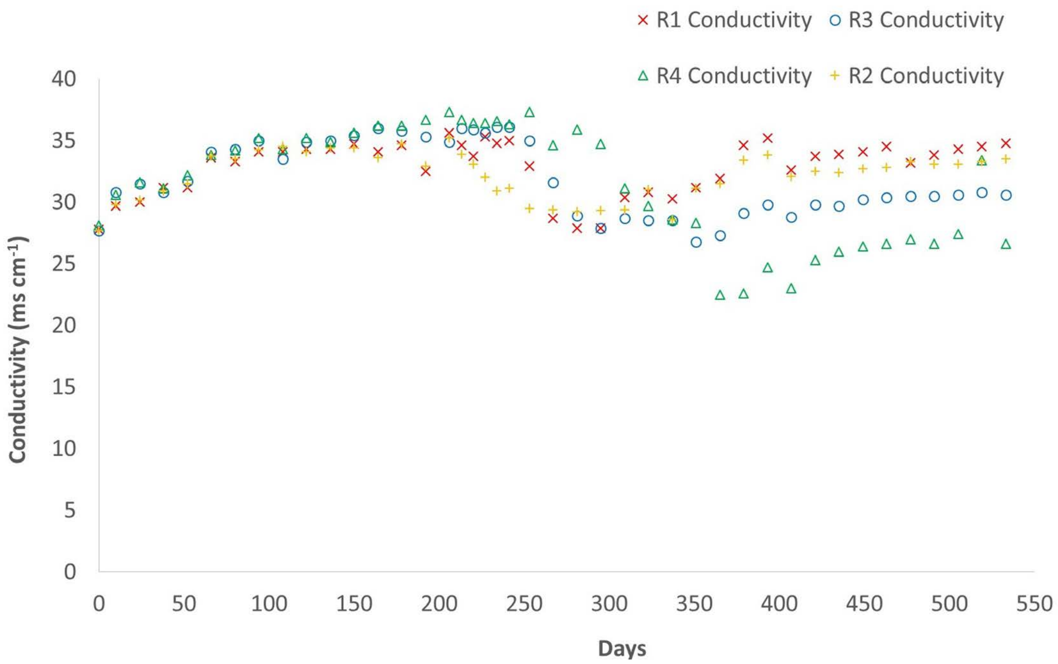

Fig. 5. Conductivity changes in reactors.

and Pb were below 0.5 mg L^{-1} in all reactors. The results may indicate that the bioreactor landfill system was effective at reducing the metal concentrations through adsorption on waste material and precipitation due to increased pH.

3.3.5. COD and BOD_5/COD ratio

COD is a similar parameter to biological oxygen demand (BOD), but the BOD test represents only the biodegradable portion of the organic matter in a water sample. However, BOD values generally show a similar trend to COD concentrations. Therefore, it provides additional information on the biodegradable fraction of the COD. Fig. 7 represents the change in COD over time for all reactors. Concentrations of COD in the leachate followed trends similar to the tVFA concentrations in all reactors. Owing to the hydrolysis of organics in MSW, COD concentrations in the bioreactors rapidly increased to 128,720; 122,320; 128,160 and 136,720 mg L^{-1} for

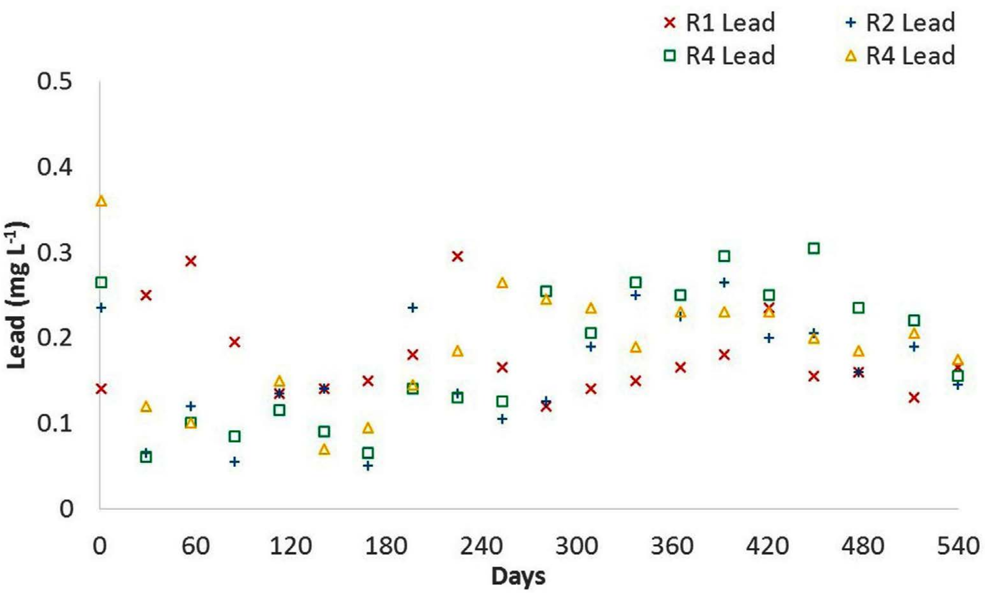

Fig. 6. Lead concentrations in reactors.

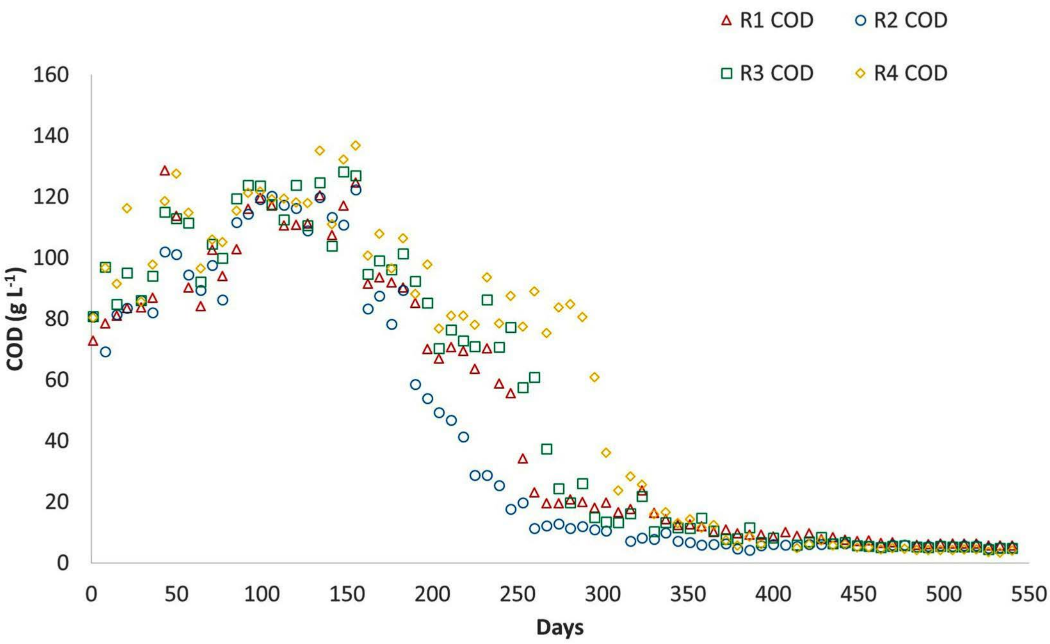

Fig. 7. COD concentrations in reactors.

R1, R2, R3, and R4, respectively. After reaching the maximum values, COD concentrations started to decrease rapidly. The final COD removal rates for all reactors were above 90%. However, the removal rate of COD was the fastest in R2, which contained geotextile (GT-1) filter and sewage sludge. The results showed that the chemical oxygen demand (COD) half life of leachate from R2 was about 218 d, which was about 34 d shorter than that of R1, 49 d shorter than that of R3, and 84 d shorter than that of R4. The geotextile filter (GT-1) used in R2 had higher permeability (113 L m^{-2} s^{-1}), higher apparent opening size (112 μm), and greater thickness (1.91 mm). GT-1 was manufactured by a needle punch method, while GT-2 and GT-3 were manufactured by a needle punch and heat bond method. Geotextiles that are manufactured by heat bonding would block the channel of water flow across the entirety of the material, which could reduce the internal porosity. Reductions in COD in the leachate during methanogenesis corresponded with increase in pH and decrease in ORP. Decrease in COD occurred along with corresponding increase in pH and decrease in ORP.

Leachate BOD_5/COD ratio is an indication of microbiological activity and organic contaminant levels in leachate. Leachates from young landfills have higher BOD_5/COD ratios than old leachates [45]. The BOD_5/COD ratio is generally used to reflect the proportion of biodegradable organic material in the leachate. The biodegradable organic compounds in the leachate, corresponding to BOD_5, are consumed by the microorganisms more easily. It was reported that young landfill leachate is characterized by an acidic phase of anaerobic biodegradation and a BOD_5/COD ratio of around 0.85, whereas older landfills have a much lower BOD_5/COD ratio of around 0.06 [46]. Acid-phase leachate possesses high concentrations of VFAs, higher ORP, and lower pH. In this study, initial BOD_5/COD ratios were 0.51, 0.37, 0.55, and 0.46 for R1, R2, R3, and R4, respectively (Fig. 8). After day 400, BOD_5/COD ratios for all reactors dropped below 0.1. The final BOD_5/COD ratios for all reactors were below 0.07. These low BOD_5/COD ratios indicate the high concentration of non-biodegradable organics and thus the difficulty of biologically degrading them. Similar BOD_5/COD ratios are reported in the literature [43,45].

3.3.6. Total volatile fatty acids

The variations in the concentrations of VFAs in the leachate usually exhibit trends similar to those of the COD concentrations. This similarity is expected since the organic fraction of the MSW is first hydrolyzed to intermediate organics and then transformed to VFAs. In all reactors, the concentration of tVFA continuously increased in the first 6 months and reached 88,438; 92,996; 70,745, and 95,199 mg L^{-1} for R1, R2, R3, and R4, respectively (Fig. 9). High tVFA concentrations in leachate indicated that the reactors remained in the acidic phase. The tVFA concentrations in the leachate of all bioreactors showed trends similar to those of COD concentrations. Specifically, the tVFA concentrations started to increase and peaked within 6 months as a result of the accumulation of organic acids. The increases of tVFA and COD may be attributable to the leachate recirculation, which could improve the contact surface area for extracellular activities to increase the solubility of organic compounds in leachate [47].

After 6 months of operation, the tVFA concentrations started to decrease, dropping below 20,000 mg L^{-1} after day 337. The low pH during the first 240 d can be attributed to the production of tVFA. The reductions of COD and tVFA after 6 months of operation indicated the occurrence of methanogens. After transition to the methanogenic phase, pH values increased because methanogens started to utilize the available tVFA as a substrate. Among the measured VFAs, acetic, butyric, and caproic acids were the dominant acids. Higher concentrations of acetic and butyric acids can be attributed to food waste in MSW [48].

3.3.7. Ammonium nitrogen (NH_4^+–N) and TKN

The majority of the nitrogen content in landfill leachate is in the form of NH_4^+–N, which is produced from the degradation of proteins and amino acids [43]. NH_4^+–N is considered one of the most significant long-term pollutants in landfill leachate because there is no mechanism to remove it from anaerobic landfills [49]. There is usually no decrease or increase in the total nitrogen concentration during anaerobic degradation of MSW in conventional landfill leachate [50]. NH_4^+–N occurs in the form of ammonium (NH_4^+) at lower pH values at which no significant adverse effect on the anaerobic process occurs, while at higher pH (>9.2), a high ammonia (NH_3) concentration may reflect an inhibitory effect on the anaerobic degradation process [51].

Fig. 10 shows the change in NH_4^+–N concentration in the leachate in the reactors. No stable trend in NH_4^+–N concentrations was detected during the study. The initial

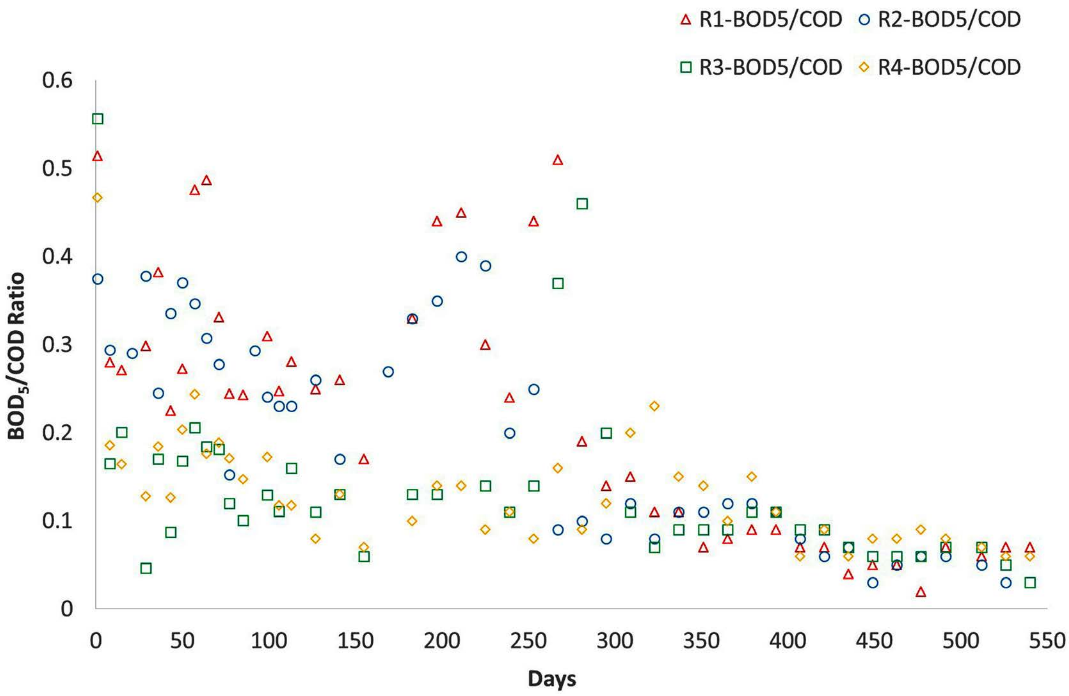

Fig. 8. BOD_5/COD ratios in reactors.

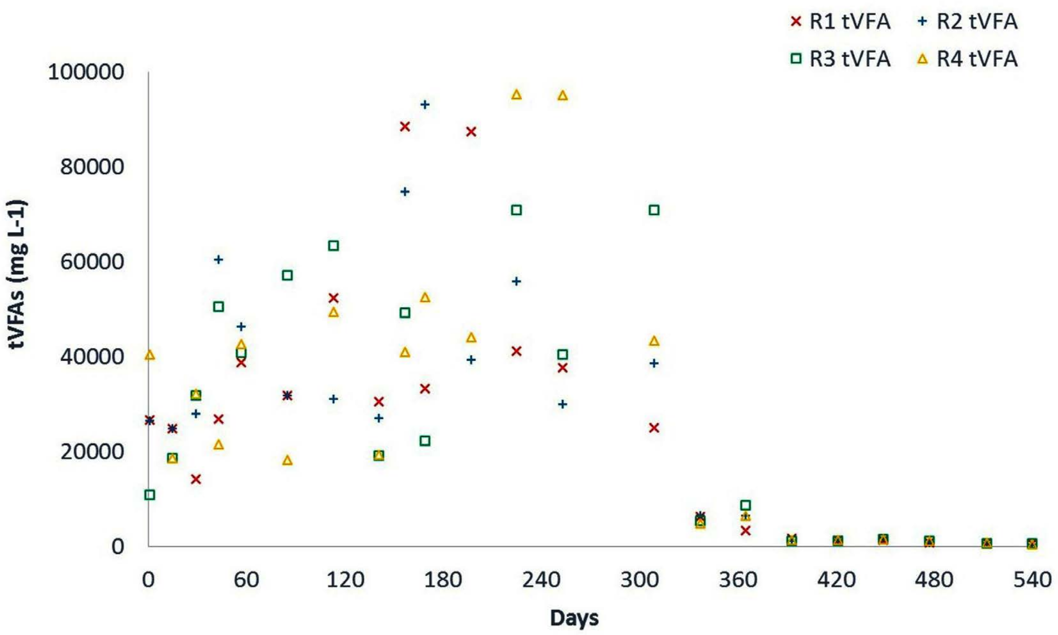

Fig. 9. tVFA concentrations in reactors.

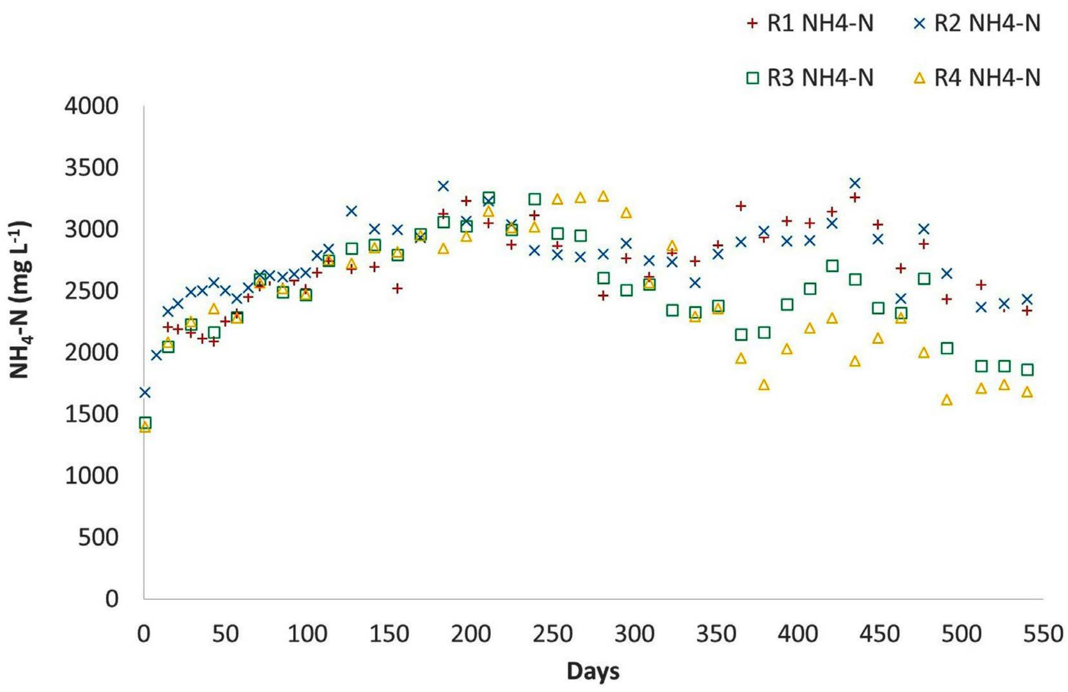

Fig. 10. NH_4^+–N concentrations in reactors.

NH_4^+–N concentrations were 1,680; 1,677; 1,433; and 1,397 mg L^{-1}, while the final NH_4^+–N concentrations were 2,430; 2,340; 1,860; and 1,680 mg L^{-1} for R1, R2, R3, and R4, respectively. At the beginning of the study, NH_4^+–N concentrations increased in all reactors. These increases might be attributable to the leachate recirculation, which washed out NH_4^+–N adsorbed in solid waste in all reactors at the beginning of the study. In addition, the protein fraction of biodegradable waste releases NH_4^+–N. The increased NH_4^+–N concentrations can intensify the toxicity of the leachate if the concentrations are above 3,000 mg L^{-1} at higher pH values. However, it was reported that NH_4^+–N levels up to 6,000 mg L^{-1} could be tolerated in anaerobic bioreactors [51]. In this study, NH_4^+–N concentrations were below toxic levels. In contrast, NH_4^+–N concentrations decreased towards the end of the study, which may be attributable to an increase in alkalinity. If no degradation pathway exists for the NH_4^+–N in landfills, then it may accumulate in the system. The initial TKN concentrations were 3,292; 2,788; 2,178; and 2,542 for R1, R2, R3, and R4, respectively (Fig. 11). An increasing trend was observed in the TKN concentrations during the operation. This increase may be attributable to the recirculation of leachate. The final TKN concentrations were determined to be 4,045; 3,710; 3,205; and 3,125 mg L^{-1} for R1, R2, R3, and R4, respectively.

3.3.8. Total alkalinity

Total alkalinity reflects the buffering capacity of water. It is a measure of the capacity of water to resist changes in pH. The higher the alkalinity, the more acid can be added without substantially reducing the pH. This is because bicarbonates and carbonates react with hydrogen ions generated by the acid, preventing them from reducing the pH. Leachate recirculation in a landfill can lead to higher alkalinity, which will then provide sufficient buffering for the pH to remain at around 7 or above. Alkalinity has an important function in anaerobic digestion. When the concentrations of acids exceed the total alkalinity, methanogenic bacteria can be inhibited, which results in system failure. As a result of the decomposition of organic waste, a considerable number of bicarbonate ions (HCO_3^-) are formed, which will increase the alkalinity in the leachate. Farquhar and Rovers [39] suggested that an anaerobic degradation process would require minimum alkalinity of 2,000 mg L^{-1} to maintain an optimal methanogenesis rate. The alkalinity values obtained in the present study were in the range of 7,975–17,150 mg $CaCO_3$ L^{-1} (Fig. 12), which are similar to those reported in the literature [34,52,53]. Leachate recirculation provided stable alkalinity in the reactors since it has positive effects on the stabilization of MSW. This consistent alkalinity of the leachate prevented the reactors from developing a severely acidic environment, which would inhibit the growth of methanogens.

3.3.9. Chloride and sulfate

Cl^- and SO_4^{2-} are inorganic anions found in landfill leachate. Cl^- ion is non-biodegradable and a persistent constituent that is generally used to estimate the dilution effects on the leachate. After the start-up period, no supplemental water was injected into the system, and the leachate produced from the reactors was recirculated periodically. Figs. 13 and 14 show the changes in Cl^- and SO_4^{2-} concentrations over time in the leachate from the reactors. The maximum Cl^- concentration was 5,098 mg L^{-1} and the minimum was 1,719 mg L^{-1} for all reactors. The decreases in leachate Cl^- concentrations were 3%, 6%, 22%, and 33% for R1, R2, R3, and R4, respectively. It can thus be asserted that the bioreactors containing a geotextile filter, but no sewage sludge achieved greater reductions in the chlorine concentration. In the literature, the mean chloride concentrations in leachate from anaerobic bioreactor landfills vary between 100 and 12,400 mg L^{-1} [54]. It was reported that Cl^- emission potentials were reduced by between 79% and 85% for aerobic, anaerobic, and aerated bioreactor landfills [26].

Concentrations of SO_4^{2-} in leachate depend on the decomposition of the organic matter present in the solid waste. Sulfur compounds are in the form of SO_4^{2-} and S^{2-} ions in the leachate samples. The initial SO_4^{2-} concentrations for all reactors were above 2,000 mg L^{-1}. However, during the methanogenic phase, the concentrations sharply decreased and remained below 1,000 mg SO_4^{2-} L^{-1} until the end of the operation. The trends

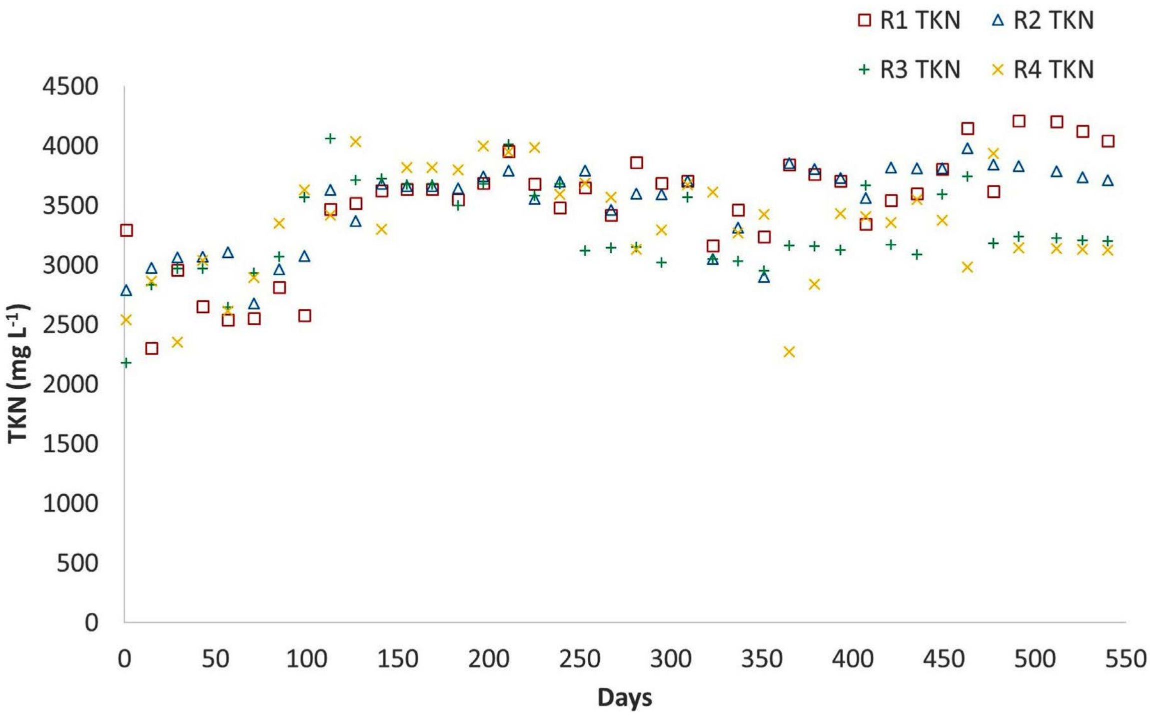

Fig. 11. TKN concentrations in reactors.

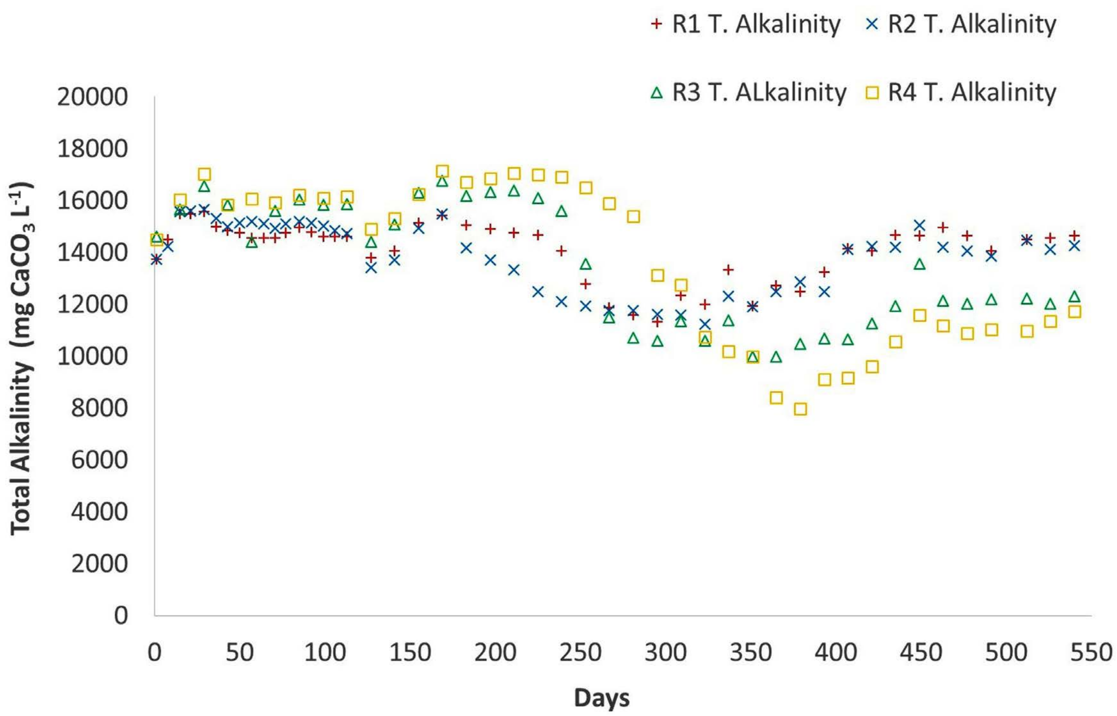

Fig. 12. Total alkalinity in reactors.

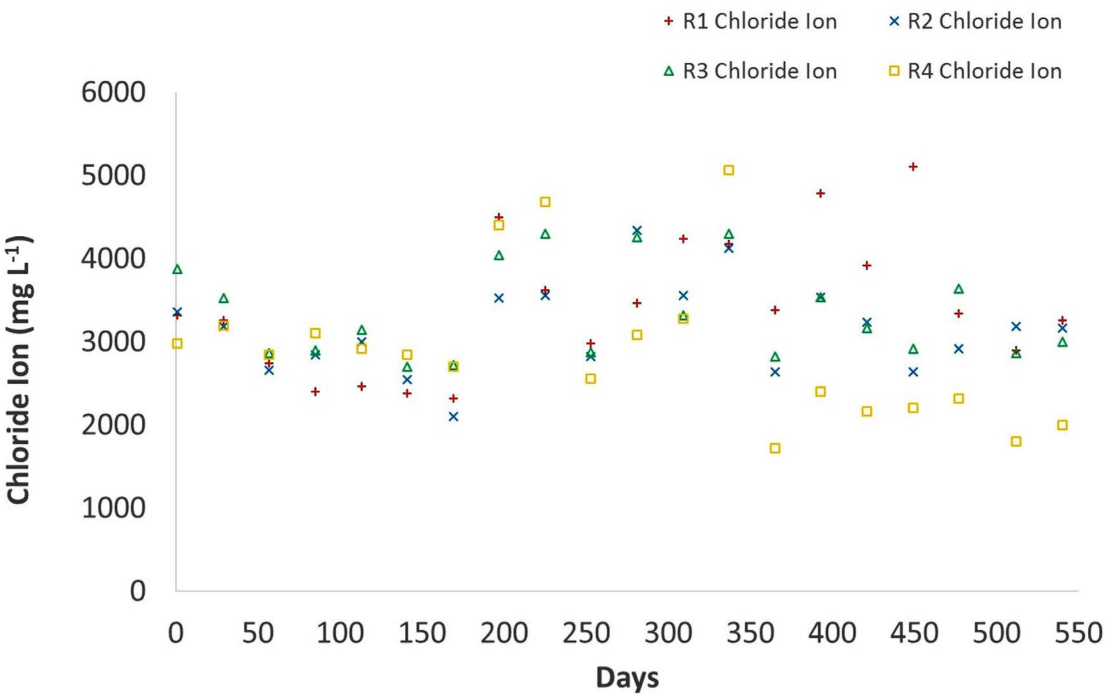

Fig. 13. Chloride concentrations in reactors.

of decreases in R1 and R2 occurred much earlier than those of R3 and R4. The SO_4^{2-} concentrations started to decrease drastically after day 200, reaching 35 mg L^{-1} for all reactors at the end of the study. These decreases were attributable to the reduction of SO_4^{2-} to S^{2-} when anaerobic conditions prevailed in the reactors. A reduction in SO_4^{2-} concentration in the leachate can also be used as an indicator of waste stabilization within the reactors. The findings indicate that 98% of the sulfate was removed in all reactors by the end of the study. Similar findings are reported in the literature [3,34].

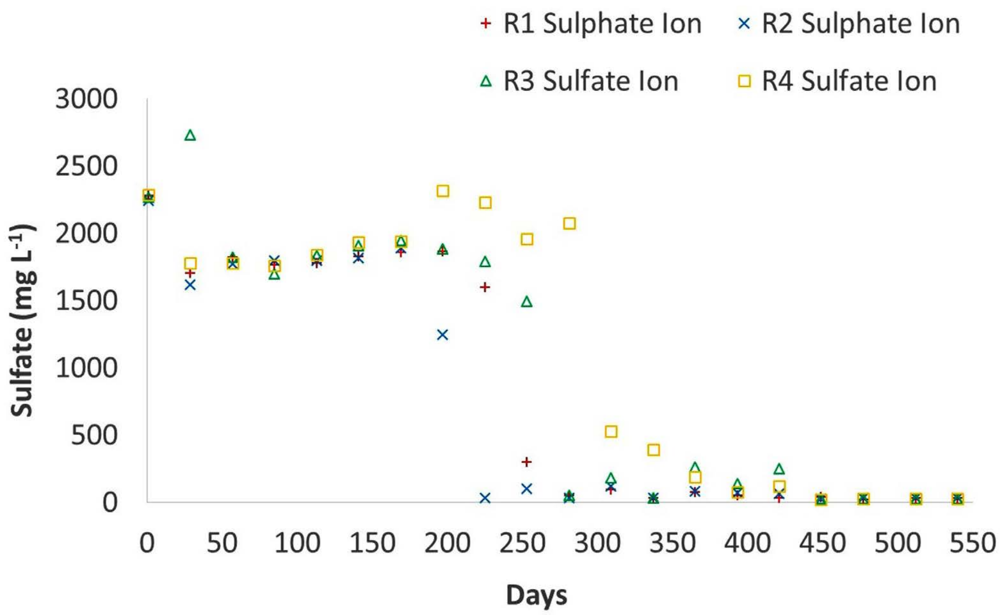

Fig. 14. Sulfate concentrations in reactors.

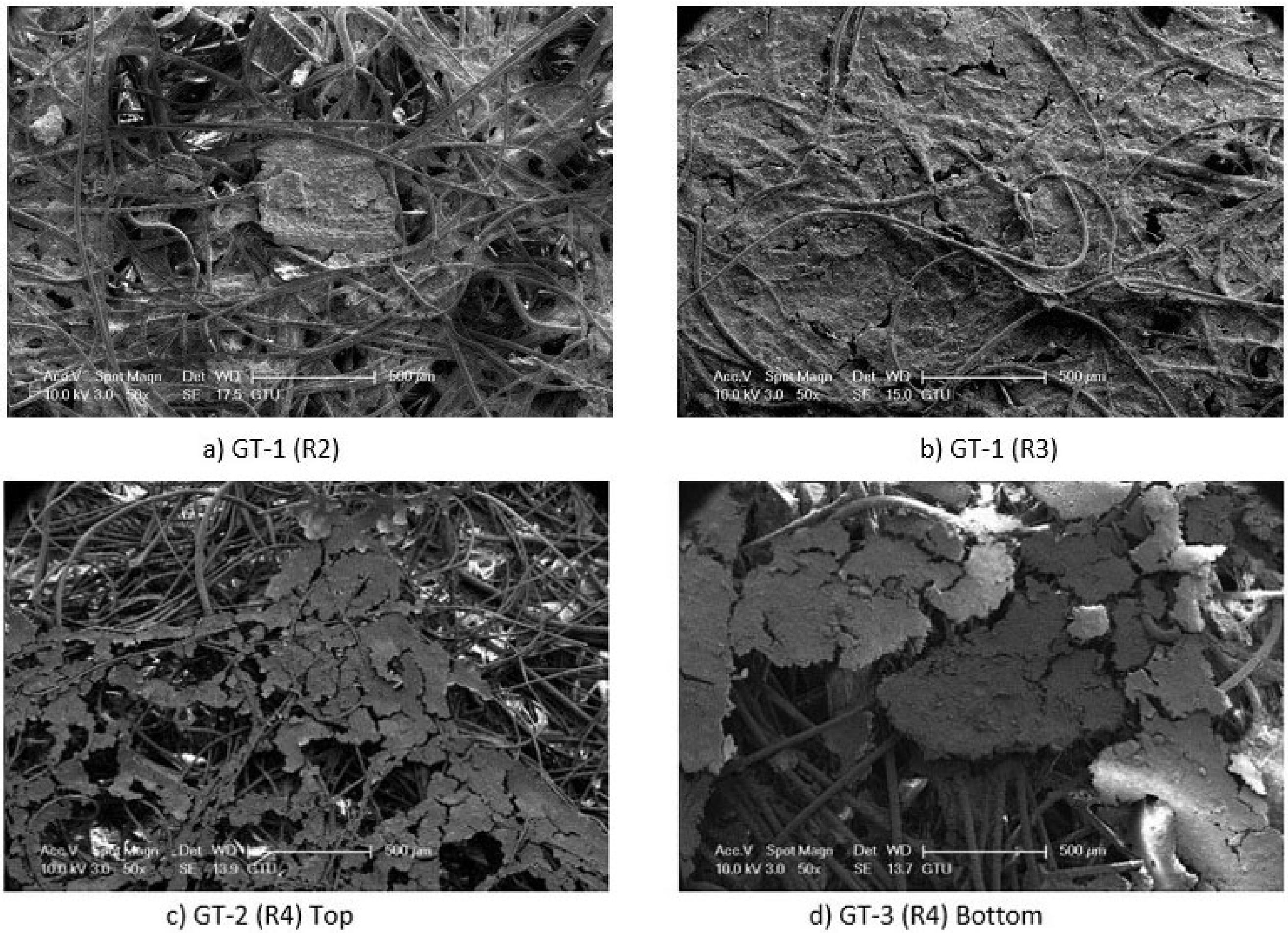

Fig. 15. SEM images of geotextile filters at 50× magnification. (a) GT-1 (R2), (b) GT-1 (R3), (c) GT-2 (R4) top, and (d) GT-3 (R4) bottom.

3.4. Microbial biomass in geotextile filters

After 540 d of operation of R2, R3, and R4, it was expected that some microbial biomass formation would have occurred on the geotextile filters. To visualize this biomass, SEM images were taken at 50× magnification from the recovered and air-dried geotextile samples from the reactors. Previous studies had demonstrated that the biomass can accumulate on either the inside of the porous structure of the non-woven geotextiles as trapped suspended "flocs" (aggregated bacterial cells) between the fibers, or as an attached biofilm on the surface area of the fibers [55]. The complex biomass structure between widely spaced geotextile fibers can be seen in Fig. 15, showing that there were some attached formations on the fibers, which may confirm biofilm formation. Fig. 15a shows GT-1, which was exhumed from R2 containing MSW and sewage sludge, while Fig. 15b shows GT-1, which was exhumed from R3 containing MSW only. Figs. 15c and d show GT-2 (upper) and GT-3 (below), which were exhumed from R4. It can be clearly seen that GT-1 in R3 contained the most biomass per surface area, followed by GT-1 in R2, and GT-2 (upper) and GT-3 (below) in R4. Since GT-1 had the highest permeability, thickness, and apparent opening size, it formed the most biomass per surface area. In addition to this, there were some visible attached particles between the pores of the geotextile samples. In a similar study, the authors reported that organic matter retained on the geotextile filters favored bacterial activity and hence the consumption of nutrients in the leachate by bacterial colonies [56]

4. Conclusion

This research was designed to upscale a laboratory bioreactor landfill system, which had been demonstrated to improve leachate quality by installation of a geotextile filter. In this study, four pilot-scale anaerobic bioreactors, 25 times the volume of the lab-scale bioreactor (1.75 m^3, as compared with 0.07 m^3), were set up, containing sewage sludge mixed with MSW (R1 and R2), with a geotextile filter fitted into its drainage layer (R2, R3, and R4), with the leachate being recirculated. R2 with sewage sludge and GT-1 had the shortest COD half life and the highest VS reduction rate among the reactors. One of the significant results of this study was that the COD half life of leachate from R2 was about 218 d, which was about 34 d shorter than that of R1, 49 d shorter than that of R3, and 84 d shorter than that of R4. This reduced COD half life can be attributed to sewage sludge and geotextile filter included in R2. In reactor 2, the addition of sewage sludge provided necessary nutrients and moisture for growth of microorganisms responsible for organic degradation, while the geotextile filter helped to reduce COD in leachate. Similar to COD half-life reduction, VSs reduction was also higher in R2 containing sewage sludge and geotextile filer. R2 showed the lowest final VS (27%) content in waste samples, which indicates higher waste stabilization. Average leachate treatment efficiencies were similar to those in lab-scale study, with a COD reduction of more than 95%. However, VS and TC reductions in final waste samples were higher in this pilot-scale study than that of the lab-scale study. Maximum TC and VS removal rates in this pilot-scale study were 66%, while the lab-scale study showed TC reduction of 52% and VS reduction of 44%.

The two-layered geotextile reactor (R4) with GT-2 and GT-3 did not perform very well in terms of COD half-life. This could be attributable to the properties of GT-3, which had lower permeability and a smaller apparent opening size, which decreased the formation of biomass, as seen in Fig. 15d.

The use of a geotextile filter with higher permeability and higher apparent opening size may shorten the COD half life and increase waste stabilization. After 540 d of operation, all of the geotextile filters were still functioning well, without signs of clogging, while SEM visualization of the geotextiles showed that they acted as substrates on which bacterial biofilms developed, possibly facilitating microbial degradation of the leachate contaminants, particularly organic components.

This model bioreactor, particularly the use of geotextile fibers, has considerable potential for in-situ leachate remediation, by wrapping geotextile around leachate collection pipes in the drainage layers. Further research is needed. For example, multiple examples of each reactor need to be constructed and tested as replicates to determine whether any apparent differences are statistically significant, while field-scale trials will also be appropriate.

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Conflicts of interest

The author has no conflicts of interest.

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