Characteristics and biogas production potential of municipal solid wastes pretreated with a rotary drum reactor

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ABSTRACT

This study was conducted to determine the characteristics and biogas production potential of organic materials separated from municipal solid wastes using a rotary drum reactor (RDR) process. Four different types of wastes were first pretreated with a commercial RDR system at different retention times (1, 2, and 3 d) and the organic fractions were tested with batch anaerobic digesters with 2.6 g VS L⁻¹ initial loading. The four types of waste were: municipal solid waste (MSW), a mixture of MSW and paper waste, a mixture of MSW and biosolids, and a mixture of paper and biosolids. After 20 d of thermophilic digestion (50 ± 1 °C), it was found that the biogas yields of the above materials were in the range of 457–557 mL g VS⁻¹ and the biogas contained 57.3–60.6% methane. The total solid and volatile solid reductions ranged from 50.2% to 65.0% and 51.8% to 66.8%, respectively. For each material, the change of retention time in the RDR from 1 to 3 d did not show significant (α = 0.05) influence on the biogas yields of the recovered organic materials. Further studies are needed to determine the minimum retention time requirements in the RDR system to achieve effective separation of organic from inorganic materials and produce suitable feedstock for anaerobic digesters.

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1. Introduction

In 2005, 42 million tons of municipal solid wastes (MSW) were landfill in California, about 64% (by wet weight) of which is of biological origin (California Integrated Waste Management Board, 2007). The organic fraction of MSW is naturally degraded over time in landfills producing various gases including greenhouse gases (Augenstein, 1992). Even though many landfills have installed landfill gas recovery systems, the whole waste management industry is still facing challenges such as limited land availability, odor and ground water pollution from leachate (Lewis et al., 2003). To reduce the amount of wastes destined for landfills, the organics from MSW can be separated and treated through conversion technologies for volume reduction and generation of valuable byproducts, such as biogas energy and compost. Composting has been a more widely applied process for treating municipal organic solids compared to anaerobic digestion. However, in the US, the economical value of the MSW-derived compost is usually low, often less than 13 US$ m⁻³, and many composting plants offer the compost for free. The increasing energy prices make the anaerobic digestion appear to be a more attractive process for achieving both waste reduction and energy recovery.

Usually it is recommended to remove a certain amount of inorganic fractions (e.g., metals and glass) in raw MSW prior to anaerobic digestion for more efficient operation of anaerobic digesters and prevention of equipment failures involved in material handling. Some pre-treatment methods may also be applied to increase the digestibility of the organic solids and increase the efficiencies of anaerobic digesters (Bernal et al., 1992). In the study reported by Capela et al. (1999), a pre-composting stage was used for the pulp mill sludge to obtain a slight degradation of organics to prevent fast acidification during anaerobic digestion. After a 49 d experiment, the pretreated sludge had higher volatile solids (VS) reduction (50%) than the untreated sludge which had 34% VS reduction. Previous studies have also shown that a rotary drum reactor (RDR) process provided an effective means for separating the organics from MSW using a combination of mechanical forces and biological reactions (Hayes, 2004; Spencer, 2006).

Thermophilic conditions have certain advantages over mesophilic conditions for digesting the organic wastes separated from MSW, such as faster degradation rate, higher biogas production rate, lower effluent viscosity, and higher pathogen-destruction...
(Cooney and Wise, 1975). Maly and Fadrus (1971) conducted batch digestion tests of activated sludge from a municipal wastewater treatment plant at 20, 30 and 50 °C. After 140 d digestion, the total biogas production and solid reduction of the sludge at different temperatures were almost identical, but the higher temperature of 50 °C resulted in higher organic degradation rate than the low temperatures. Cecchi et al. (1990, 1991) compared the biogas production of the organic solid waste at mesophilic (37 °C) and thermophilic (55 °C) conditions using a 3 m³ continuous stirred-tank reactor (CSTR). The organic waste was separated from household MSW and contained TS and VS of 76% and 34%, respectively. The reactor (CSTR). The organic waste was separated from household MSW and contained TS and VS of 76% and 34%, respectively. The mesophilic experiment was conducted under the organic loading rate (OLR) of 7.5 g VS L⁻¹ d⁻¹ and hydraulic retention time (HRT) of 14.7 d and the biogas yield achieved was 200 ml g VS⁻¹ and VS reduction was 23%. The thermophilic experiment was conducted at OLR of 6.9 g VS L⁻¹ d⁻¹ and HRT of 11.7 d and the biogas yield was 410 ml g VS⁻¹ biogas yield and 43% VS reduction. But when the OLR was increased to 9.2 g VS L⁻¹ d⁻¹, the thermophilic system was found to be overloaded due to noticeable reduction in biogas yield (290 ml g VS⁻¹) and VS reduction (34%). A number of studies have recently been reported in the literature on the anaerobic digestion of food processing wastes and grocery organic wastes (Cho et al., 1995; Mata-Alvarez et al., 1992, 2000; Viswanath et al., 1992; Rao et al., 2000), with the reported biogas yield being in the range of 661–796 ml g VS⁻¹ and the methane content of 52–70%. Zhang et al. (2007) reported the thermophilic digestion of food wastes separated from restaurant wastes. The average biogas yield and VS reduction in the food waste after 28 d of digestion were determined to be 600 ml g VS⁻¹ and 81%, respectively. About 80% of the biogas was produced in the first 10 d of digestion with the biogas yield being 480 ml g VS⁻¹ and methane content of biogas being 73%.

The present study was carried out to evaluate the anaerobic digestibility and biogas production potential of the organic materials separated from MSW using the RDR process. The specific objectives of this study were to characterize the organic materials separated from different types of solid waste available in municipalities by a RDR process operated at different retention times, to determine their anaerobic digestibility and biogas production potential, and to assess their suitability for use as feedstock for anaerobic digestion systems.

2. Methods

2.1. Description of the rotary drum reactor (RDR) process

The RDR used for this study was at a commercial MSW treatment facility in Arizona, US, where the MSW collected from local community and biosolids generated from the city wastewater treatment plant were co-composted. The RDR process used in this study comprised a rotary drum reactor of 3 m diameter and 38 m length followed by a trommel screen with 31.8 mm openings (Fig. 1). It was used to process 20–30 t d⁻¹ of MSW, cardboard and paper waste, and biosolids with an average retention time of 3 d. Air was blown into the drum to enhance the aerobic microbial activities. The drum was foam insulated to keep the temperature at 45–68 °C. The material discharged from the rotary drum was passed through the trommel screen with the finer size fraction being collected through the screen and the coarser size fraction being collected on the screen. The finer fraction contains mainly biodegradable organic materials and was sent to windrow composting and the coarse fraction contains mainly non-biodegradable organic (e.g., plastics) and inorganic (e.g., metals, glass) materials and was sent to a landfill. The fines account for 50–55% of the original weight of material and have a moisture content of 55–60%.

2.2. Experimental setup, sample collection and analysis

The experiments for this study were designed to examine the characteristics of the organic materials (fines) produced by RDR, as affected by different types of waste and retention times in the RDR. To accomplish this, the RDR was operated for a week from February 26 to March 4, 2007, with four different waste types: MSW, mixture of MSW and cardboard and paper waste, mixture of MSW and biosolids, and mixture of cardboard and paper waste and biosolids. Cardboard and paper waste was here referred to as simply paper. For each type of waste, three retention times (1, 2 and 3 d) were evaluated. The weight and composition of the four waste types tested are shown in Table 1.

According to the regular RDR operational protocols, the desired moisture content of the material entering the drum should be about 55%, wet basis. Therefore, water was added to MSW and to the mixture of MSW and paper to bring the moisture content to this value. No water was needed for the mixtures containing biosolids because the moisture content of biosolids was already high, about 82%. The average speed by which the waste traveled inside the drum was controlled by the loading and unloading rates. This speed was kept constant at approximately 1/3 of the drum length each day, or 0.53 m h⁻¹. One waste type was introduced into the drum each day, with the simultaneous unloading of pretreated material from the exit of the drum. Thus one third of the drum was occupied by fresh waste everyday and there was no back-mixing observed before wastes were discharged from the other end of the drum. Samples were collected every day from the drum exit and two sampling ports located at 1/3 and 2/3 drum length from the entrance. A total of 12 samples were collected from the drum, corresponding to the above mentioned four different waste types with three retention times in the drum for each waste type. All the samples collected from the rotary drum were screened on-site using a trommel screen of 31.8 mm openings to remove the large size fraction (mainly non-biodegradable materials). The recovery of organic materials (fines) from 3-d RDR treated solid wastes was calculated (Table 2). The screened samples were packed on

<table>
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<tr>
<th>Waste type</th>
<th>Amount</th>
<th>Water (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSW</td>
<td>9400</td>
<td>3600</td>
</tr>
<tr>
<td>MSW and paper</td>
<td>6800</td>
<td>3200</td>
</tr>
<tr>
<td>MSW and biosolids</td>
<td>15,000</td>
<td>10,500</td>
</tr>
<tr>
<td>Paper and biosolids</td>
<td>6500</td>
<td>7800</td>
</tr>
</tbody>
</table>
ice and shipped overnight to the Bioenvironmental Engineering Research Laboratory at the University of California, Davis (UC, Davis). The samples were then put into a freezer for storage at –20 °C until analyses. Prior to the anaerobic digestion tests, samples were manually screened using a stainless steel screen with 6.4 mm openings to remove the large glass and metal particles in order to fit the samples into the anaerobic reactors for biogas and methane yield measurements.

Two sets of analyses were performed on the collected samples. The samples collected from 3-d retention time trials were analyzed in greater detail than the samples collected with 1-d and 2-d retention time trials because the 3-d retention time is the current standard for the RDR plant used for this study. The analyses performed for different samples are shown in Tables 2–4. All the elemental analyses and the measurements of the various carbohydrates, lignin, NH4–N and NO3–N concentrations were performed by the DANR laboratory of UC Davis based on the standard laboratory protocols (ANR analytical lab, 2007). The rest of the analyses were carried out at the Bioenvironmental Engineering Research Laboratory of UC Davis, using standard methods (APHA, AWWA and WEF, 1998; Legee and Thompson, 1997). The experimental procedures for determining the biogas and methane production potential using batch anaerobic digestion tests are described below.

### 2.3. Anaerobic digestion tests

The biodegradability and biogas production potential of the waste samples collected from the RDR process were determined using batch anaerobic digestion tests as described in Anaerobic Lab Work (2000). The digestion was carried out in 1 L glass bottles (KIMAX® No. 14397, USA) at 50 ± 1 °C. Digestion tests were performed in duplicate on the 12 waste samples along with a food waste sample which was used for comparison. The food waste was collected from a student cafeteria on the campus of University of California, Davis, and consisted predominantly of leftover food.

The inoculum sludge used in the digestion tests was collected from thermophilic anaerobic digesters at a municipal wastewater treatment plant in Oakland, California. The TS, VS, VS to TS ratio (VS/TS) and pH of the anaerobic sludge were measured to be 2.47%, 1.48%, 0.60, and 6.74, respectively.

Each batch reactor was initially loaded with 150 mL inoculum sludge, waste sample containing 2.85 g VS, and 342 mL distilled water to achieve a food to microorganism ratio (F/M) of 1.2 and

<table>
<thead>
<tr>
<th>Table 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characteristics of organic materials recovered from municipal solid wastes using the RDR process with different retention times (characteristics of food waste are included for comparison)</td>
</tr>
<tr>
<td>Waste type</td>
</tr>
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</tr>
<tr>
<td>MSW</td>
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<td>Paper and Biosolids</td>
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<td></td>
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<tr>
<td>Food Waste</td>
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</table>

* Organic recovery for 1 and 2 d retention time in the RDR were not determined.

<table>
<thead>
<tr>
<th>Table 3</th>
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<tr>
<td>Compositions of organic materials recovered from different types of municipal solid wastes via RDR process at 3 d retention time</td>
</tr>
<tr>
<td>Parameters</td>
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<tr>
<td>---</td>
</tr>
<tr>
<td>Cellulose</td>
</tr>
<tr>
<td>Hemi-cellulose</td>
</tr>
<tr>
<td>Lignin</td>
</tr>
<tr>
<td>Starch</td>
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<tr>
<td>Glucose-total</td>
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<tr>
<td>Fructose</td>
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<tr>
<td>Sucrose</td>
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<tr>
<td>Total nonstructural carbohydrates (TNC)</td>
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<tr>
<td>Total kjeldahl nitrogen (TKN) ppm</td>
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<tr>
<td>Nitrate nitrogen (NO3–N) ppm</td>
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<tr>
<td>Nitrate nitrogen (NO3–N) ppm</td>
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</table>

The results listed in this table are based on dry weight.

<table>
<thead>
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<th>Table 4</th>
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<tr>
<td>Element concentrations in organic materials recovered from different types of municipal solid wastes via RDR process at 3 d retention time</td>
</tr>
<tr>
<td>Parameters</td>
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<td>Phosphorus (P) ppm</td>
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<td>Magnesium (Mg) ppm</td>
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<td>Aluminum (Al) ppm</td>
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<td>Zinc (Zn) ppm</td>
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<td>Manganese (Mn) ppm</td>
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<td>Copper (Cu) ppm</td>
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<tr>
<td>Cadmium (Cd) ppm</td>
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<td>Chromium (Cr) ppm</td>
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<td>Cobalt (Co) ppm</td>
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<td>Lead (Pb) ppm</td>
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<td>Molybdenum (Mo) ppm</td>
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<td>Nickel (Ni) ppm</td>
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<tr>
<td>Selenium (Se) ppm</td>
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<tr>
<td>Arsenic (As) ppm</td>
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</table>

The results listed in this table are based on dry weight.
a working volume of 500 mL. The F/M was calculated by dividing the feedstock VS by the inoculum VS. Each reactor was tightly closed with a rubber septa and a screw cap. To assure anaerobic conditions, the head space of each reactor was purged with helium gas for five minutes. Two blank reactors were used to correct for the biogas produced from the inoculum. Each blank reactor contained 150 mL anaerobic sludge and 340 mL distilled water.

2.4. Biogas production and composition measurement

Biogas production was estimated daily by measuring the pressure in the head space of each reactor and then converting to volume by application of the ideal gas law. Pressure was measured using a membrane pressure gauge (Model 3150, WAL Mess-und Regeltechnik GmbH, Germany). After the pressure measurement, the biogas in the head space was released under water. Then the pressure in the head space was measured again as an initial condition for the next-day measurement. Daily pressure differences were converted into biogas volume as:

\[
V_{\text{biogas}} = \frac{(P_2 - P_1) \cdot T_2}{P_a \cdot T_1} \cdot V_1
\]

where

- \( V_{\text{biogas}} \) = volume of daily biogas production (mL);
- \( P_1 \) = post-release headspace pressure of the previous day (kPa);
- \( P_2 \) = headspace pressure before biogas release (kPa);
- \( P_a \) = ambient pressure (kPa);
- \( T_1 \) = headspace pressure before biogas release (kPa);
- \( T_2 \) = temperature of the reactor (K);
- \( V_1 \) = headspace volume (mL).

Daily biogas yield was determined by dividing the volume of biogas produced each day by the initial VS loaded into the reactor. Cumulative biogas yield was calculated by summing the daily biogas yields at the end of each test.

The biogas composition (H\(_2\), CH\(_4\) and CO\(_2\)) of each reactor was measured daily using a gas chromatograph (GC) (Agilent 6890 N) equipped with a thermal conductivity detector (TCD) and packed column (Alltech C-9000) of length 3.05 m, outside diameter 3.18 mm, internal diameter 2.16 mm and with 80/100 mesh carbosphere. The carrier gas was argon at a flow rate of 30.8 mL min\(^{-1}\). The injector, oven and detector temperatures were 120, 100 and 120 °C, respectively.

2.5. Kinetic and Statistical analyses

A kinetic model modified from the Gompertz growth equation (Schnute, 1981; Zwietering et al., 1990) was proposed to determine the biogas yield potential as follows:

\[
\text{BG} = \text{BGP} \exp \left\{ - \exp \left[ \frac{R_m e}{\text{BGP}} (\lambda - t) + 1 \right] \right\}
\]

where

- \( \text{BG} \) = cumulative biogas yield (mL g VS\(^{-1}\)),
- \( t \) = digestion time (d),
- \( \text{BGP} \) = biogas yield potential (mL g VS\(^{-1}\)),
- \( R_m \) = maximal daily biogas yield (mL g VS\(^{-1}\) d\(^{-1}\)),
- \( \lambda \) = bacteria growth lag time (d),
- \( e \) = mathematical constant (2.718).

BGP, \( R_m \) and \( \lambda \) were determined using single Levenberg–Marquardt iteration by Origin 7.5 (Originlab Corporation, Northampton, MA 01060).

Statistical analyses were performed using Statistics Analysis System software (SAS, version 9.1) to determine if there were significant differences in terms of cumulative biogas yield and biogas yield potential for different retention times used in the RDR (1, 2 or 3 d). The significance test was based on Tukey’s studentized range test and least significant difference (\( x = 0.05 \)).

3. Results and discussion

3.1. Characteristics of the organic materials produced from RDR

The moisture content, VS/TS and TN, C/N and pH of all the samples analyzed are shown in Table 2. The moisture content of the samples varied from 49.8% to 59.6%. Generally, longer retention time in the drum resulted in lower moisture content in the organic material, most likely due to the moisture loss under the forced aeration. In comparison, the food waste had a moisture content of 74.4 ± 1.8%.

The VS/TS of all the RDR pretreated waste samples were in the range of 69.2–80.0%. Theoretically, longer retention time in the drum could result in lower VS/TS because it was expected that biodegradable organics are removed from the waste due to the biological oxidation inside the rotary drum. However, measurements did not support this prediction. For each type of waste, VS/TS changed less than five percentage points with extension in retention time, indicating that the loss of volatile matter during pre-treatment was small. Organic materials separated from the mixture of paper and biosolids resulted in the highest VS/TS, which may be attributed to the fact that biosolids and paper waste contained more volatile matter compared to MSW. Regarding all the RDR treated wastes, the VS/TS values were lower than that of food waste (96.4%), as expected. Similar to the VS/TS, the TC values of the samples were fairly consistent (40.3–43.4%). The TC of food waste was approximately 20% higher than that of the RDR waste samples.

For a particular waste type pretreated in the RDR for different retention times, the TN contents of the recovered organics were similar. The organic material produced from the wastes containing biosolids had slightly higher TN (1.5–1.9%) and lower C/N (21.1–26.7) than the organic material from the wastes containing no biosolids (1.1–1.6% TN and 26.2–36.6 C/N). The C/N values of all the organic materials recovered were considered to be appropriate for anaerobic digestion, as they were in the optimum range of 20–30 reported by McCarty (1964). In comparison, the food waste had TN of 6.9% and C/N of 7.2.

The pH of the organic materials recovered from 1-d retention time in RDR was 6.0–7.5, with an average of 7.1. The pH of the materials recovered from 3-d retention time in RDR was 5.4–6.2, with an average of 5.9. As a general observation from Table 2, the pH decreased in most cases along with the retention time in the RDR. In comparison, the pH of the food waste was 4.2.

Compositions and elemental analyses of the organic materials recovered from four different waste types with 3-d retention time in RDR are shown in Tables 3 and 4. The compositions and elements of the four different wastes were also similar except that the wastes containing biosolids showed higher total kjeldahl nitrogen (TKN) and ammonia–nitrogen (NH\(_4\)-N).

3.2. Biogas yield and biogas yield potential

The biogas production potential is presented in terms of biogas yield, methane content and methane yield. The results of daily and cumulative biogas yields are shown in Figs. 2–6. Biogas production after the 15th day of digestion was negligible, and most of the biogas was produced during the first 10 d of digestion. Regarding all the RDR treated wastes, the peak value of daily biogas yield usually occurred on the 4th day of digestion.
For the MSW samples with different retention times in the rotary drum, the daily and cumulative biogas yields are presented in Fig. 2. The daily biogas yields appeared to decrease slightly with the increase of retention time in the drum, probably due to the aerobic degradation of organics occurring in the drum. The peak values were calculated to be 131, 121 and 97 mL g VS$^{-1}$ day$^{-1}$, for 1, 2 and 3 d retention times in the RDR, respectively. The cumulative biogas yields were calculated to be 521, 502 and 466 mL g VS$^{-1}$, respectively.

Similar trends were found for the biogas yields of RDR treated MSW and paper mixtures (Fig. 3). The peak values of daily biogas yield were 124, 116 and 100 mL g VS$^{-1}$ day$^{-1}$, for 1, 2 and 3 d retention times. The cumulative biogas yields did not vary significantly ($\alpha = 0.05$) with the retention time in RDR, as they were determined to be 485, 526 and 516 mL g VS$^{-1}$, respectively.

As shown in Fig. 4, the daily biogas yields of the waste samples produced from mixtures of MSW and biosolids showed minor differences. The peak values for 1, 2 and 3 d retention times in the drum were 119, 126 and 110 mL g VS$^{-1}$ day$^{-1}$, respectively, on the 4th day of digestion. The cumulative biogas yields were 557, 534 and 492 mL g VS$^{-1}$, respectively. Compared with the other three types of RDR treated wastes, the cumulative biogas yields for the MSW and biosolids mixtures were clearly higher. The combination of MSW with biosolids appears to be more favorable for biogas production compared to the other combinations, possibly because of comparatively higher nitrogen content.

The samples produced from the mixture of paper and biosolids had the lowest biogas yields (Fig. 5) among all the samples evaluated. The peak values of daily biogas yield were 98, 125 and 111 mL g VS$^{-1}$ day$^{-1}$, respectively, while the cumulative biogas yields were 457, 507 and 504 mL g VS$^{-1}$, respectively. This may be attributed to the fact that cellulose contained in paper is more difficult to digest than other organics contained in MSW (Müller et al., 2004).
As a comparison, the daily and cumulative biogas yields of the food waste are shown in Fig. 6. The main difference between food waste and RDR treated solid wastes lay in the daily biogas yield and the duration of the anaerobic digestion process. The biogas production duration of food waste was prolonged, with lower daily biogas yields (peak value: 90 mL g VS\(^{-1}\) day\(^{-1}\)) compared to the four RDR treated wastes. However, the cumulative biogas yield of the food waste (609 mL g VS\(^{-1}\)) was significantly (\(z = 0.05\)) higher than the cumulative biogas yields obtained from the RDR treated wastes. Higher cumulative biogas yield with lower daily biogas yield was expected for food waste, as food waste contained more protein compared to the organic materials in MSW and paper. According to Bushwell's formula (Symons and Bushwell, 1933), proteins have higher biogas production potential but lower degradation rates compared to carbohydrates.

The non-linear regression on the cumulative biogas yield and digestion time (Table 5) shows that the Gompertz growth equation fitted the experimental results well. With the RDR retention time extended from 1 to 3 d, the biogas yield potential of the pretreated MSW decreased from 522 to 482 mL g VS\(^{-1}\) and the maximum daily biogas yield decreased from 97 to 72 mL g VS\(^{-1}\) d\(^{-1}\). The results of statistical analyses also showed significant (\(z = 0.05\)) differences in these parameters. These facts indicated that the longer retention time in RDR could lead to the higher loss of biodegradable compounds in the MSW. Similar trends were shown in the results for the mixture of MSW and paper, with the biogas yield potential decreasing from 582 to 532 mL g VS\(^{-1}\) and maximum daily biogas yield (\(R_{\text{m}}\)) from 99 to 83 mL g VS\(^{-1}\) d\(^{-1}\). Therefore 1-d retention time in the RDR is preferred for obtaining good biogas yields and production rates. For the mixture of MSW and paper, 2-d retention time resulted in slightly higher biogas yield potential of 532 mL g VS\(^{-1}\), maximum daily yield of 93 mL g VS\(^{-1}\) d\(^{-1}\), as compared to 1- and 3-d retention times. For the mixture of paper and biosolids, the biogas yield potential increased from 457 to 510 mL g VS\(^{-1}\) when the retention time in the RDR varied from 1 to 3 d and the maximum daily biogas yield (\(R_{\text{m}}\)) increased from 73 to 86 mL g VS\(^{-1}\) d\(^{-1}\). The reason may be that the cellulosic compounds in the paper need longer retention time in the RDR to become more digestible. Compared with RDR pretreated solid wastes, food waste showed higher biogas yield potential (613 mL g VS\(^{-1}\)).

Based on the results of Tukey’s significance test (Table 6), for each type of RDR treated waste, no significant difference (\(P < 0.05\)) was found among the experimental biogas yields for the samples collected under different RDR retention times (1, 2 and 3 d). Since a shorter retention time in the RDR translates to a smaller size of rotary drum and better economics, 1-d retention time in the rotary drum is recommended for providing the pretreatment of MSW prior to anaerobic digestion. Further research needs to be carried out in order to determine if the retention time in the drum could be further reduced (i.e., whether simple separation might be equally beneficial). This study did not quantify the separation or recovery efficiencies of organic materials separated from the wastes which were treated by RDR with different retention times. The effect of the retention time in RDR on organic recovery needs to be investigated in the future research. A final

### Table 5

<table>
<thead>
<tr>
<th>Waste type</th>
<th>Retention time in RDR (d)</th>
<th>Biogas yield potential(^{1}) (BGP) (mL g VS(^{-1}))</th>
<th>Maximal daily biogas yield ((R_m)) (mL g VS(^{-1}) d(^{-1}))</th>
<th>Bacteria growth lag time ((\lambda)) (d)</th>
<th>Correlation coefficient (R^2)</th>
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<tr>
<td>MSW</td>
<td>1</td>
<td>522(^{a})</td>
<td>97</td>
<td>1.2</td>
<td>0.983</td>
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<td></td>
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<td>509(^{b})</td>
<td>87</td>
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<td>487(^{a})</td>
<td>94</td>
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<td>0.981</td>
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<td>93</td>
<td>1.7</td>
<td>0.996</td>
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<tr>
<td></td>
<td>3</td>
<td>516(^{b})</td>
<td>84</td>
<td>1.8</td>
<td>0.998</td>
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<tr>
<td>MSW and biosolids</td>
<td>1</td>
<td>562(^{d})</td>
<td>99</td>
<td>1.2</td>
<td>0.982</td>
</tr>
<tr>
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<td>550(^{a})</td>
<td>93</td>
<td>1.3</td>
<td>0.983</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>532(^{c})</td>
<td>83</td>
<td>1.7</td>
<td>0.996</td>
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<tr>
<td>Paper and biosolids</td>
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<td>457(^{a})</td>
<td>73</td>
<td>1.1</td>
<td>0.980</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>510(^{b})</td>
<td>83</td>
<td>1.3</td>
<td>0.989</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>510(^{b})</td>
<td>86</td>
<td>1.7</td>
<td>0.996</td>
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<tr>
<td>Food waste</td>
<td>–</td>
<td>613</td>
<td>80</td>
<td>0.9</td>
<td>0.989</td>
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</table>

\(^{1}\) Values within the same type of waste followed by different letters are significantly different at \(P < 0.05\).

### Table 6

TS and VS reduction and biogas and methane yields of organic materials recovered from different types of municipal solid wastes via RDR process

<table>
<thead>
<tr>
<th>Waste type</th>
<th>Retention time in RDR (d)</th>
<th>Feedstock TS reduction (%)</th>
<th>Feedstock VS reduction (%)</th>
<th>Biogas yield(^{1}) (mL g VS(^{-1}))</th>
<th>Methane yield(^{1}) (mL g VS(^{-1}))</th>
<th>Methane content of biogas (%)</th>
</tr>
</thead>
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<tr>
<td>MSW</td>
<td>1</td>
<td>52.3</td>
<td>59.0</td>
<td>520(^{a})</td>
<td>298</td>
<td>57.3</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>60.1</td>
<td>63.9</td>
<td>502(^{a})</td>
<td>300</td>
<td>59.9</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>65.0</td>
<td>66.8</td>
<td>466(^{d})</td>
<td>282</td>
<td>60.6</td>
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<td>1</td>
<td>48.4</td>
<td>53.8</td>
<td>485(^{d})</td>
<td>282</td>
<td>58.2</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>56.5</td>
<td>57.2</td>
<td>526(^{c})</td>
<td>313</td>
<td>59.8</td>
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<tr>
<td></td>
<td>3</td>
<td>58.8</td>
<td>62.6</td>
<td>516(^{b})</td>
<td>308</td>
<td>59.9</td>
</tr>
<tr>
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<td>60.0</td>
<td>64.2</td>
<td>557(^{d})</td>
<td>320</td>
<td>57.3</td>
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<tr>
<td></td>
<td>2</td>
<td>54.5</td>
<td>57.0</td>
<td>534(^{e})</td>
<td>319</td>
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<tr>
<td></td>
<td>3</td>
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<td>69.3</td>
<td>492(^{d})</td>
<td>296</td>
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<tr>
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<td>57.5</td>
<td>457(^{a})</td>
<td>261</td>
<td>57.2</td>
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<tr>
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<td>50.2</td>
<td>51.8</td>
<td>507(^{a})</td>
<td>300</td>
<td>59.4</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>52.2</td>
<td>58.8</td>
<td>504(^{d})</td>
<td>304</td>
<td>60.3</td>
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<tr>
<td>Food waste</td>
<td>–</td>
<td>86.0</td>
<td>88.1</td>
<td>609</td>
<td>350</td>
<td>57.5</td>
</tr>
</tbody>
</table>

\(^{1}\) Values within the same type of waste followed by different letters are significantly different at \(P < 0.05\).
recommendation for the retention time in RDR for a specific type of waste should be based on combined considerations of both the organic recovery through RDR process and biogas yield of the organic material recovered from wastes.

3.3. Methane content of biogas and methane yield

For the RDR treated wastes, biogas methane concentrations showed similar trends for different retention times in the drum (Fig. 7). On the first day of anaerobic digestion, the methane contents were around 52%, with trace amounts of hydrogen. After the second day, the methane contents stabilized at about 61%, while headspace hydrogen concentration was negligible. It must be noted that the experimental conditions for this study were designed for complete biomass degradation. Bio-hydrogen production could be distinct if higher initial loading rate had been selected. The methane content of biogas produced by food waste continued increasing from 37% to 68% until the 11th day of digestion.

The methane yields of RDR treated wastes and food waste were calculated (Table 6) from daily biogas yield and methane content of biogas. The methane yields of RDR treated wastes were in the range of 261–320 mL g VS\textsuperscript{-1}, while food waste presented higher methane yield of 350 mL g VS\textsuperscript{-1}. Among the four types of solid wastes evaluated in this study, the organic material recovered from RDR treated mixtures of MSW and biosolids showed the highest methane production potential of 320 mL g VS\textsuperscript{-1}.

3.4. Solids reduction

As shown in Table 6, the organic materials separated from MSW presented the highest TS and VS reduction which were in the range of 52.3–65.0% and 59.0–66.8%, respectively. The mixture of paper and biosolids showed the lowest TS and VS reductions of 50.2–55.3% and 51.8–58.8% between the RDR treated wastes and food wastes. The wastes containing biosolids showed comparatively higher TS and VS reduction than the wastes containing paper. The above results suggest that MSW consists of more easily biodegradable materials than biosolids and paper. Food waste presented higher TS and VS reduction (86.0% and 88.1%, respectively) than all the RDR treated wastes.

4. Conclusions

The results of this study showed that the RDR process could be used as an effective technology for separation and pre-treatment of the organic materials in MSW prior to anaerobic digestion. For the four types of waste materials studied, the organic fractions recovered from the RDR process showed similar characteristics with regard to the anaerobic digestion, in terms of biogas and methane yields which ranged 457–557 mL g VS\textsuperscript{-1} and 261–320 mL g VS\textsuperscript{-1}, respectively, after 20 d digestion at 50 ± 1°C. Methane content of biogas ranged from 57.3% to 60.6%. The organic material recovered from the mixture of MSW and biosolids with 1-d retention time in the RDR showed the highest biogas yield (557 mL g VS\textsuperscript{-1}), while the organic material recovered from paper and biosolids mixture with 1-d retention time in the RDR showed the lowest biogas yield (457 mL g VS\textsuperscript{-1}). About 90% of the total biogas yield was achieved in the first 10 d of digestion for most of the samples. The TS and VS reductions in the various RDR treated wastes after 20 d anaerobic digestion were 48.4–65.0% and 51.8–69.3%, respectively. The biogas yield potential estimated by the nonlinear Gompertz equation showed significant decrease (\(x = 0.05\)) on the wastes that contained papers when the retention time in RDR varied from 1 to 3 d. One-day retention time is preferable among the three retention times tested based on the test results of organic fractions as shorter retention time translates to either smaller drums or fewer drums and better economics. However, further studies are recommended to determine the minimum retention time requirements in the drum for different types of wastes, and to assess the separation efficiencies of the organic fraction under different retention times.

Acknowledgements

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References


